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A BIOMECHANICAL AND PHYSIOLOGICAL EVALUATION OF FATIGUE IN DISTANCE RUNNING

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SHARON ANN EVANS

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ABSTRACT

A BIOMECHANICAL AND PHYSIOLOGICAL
EVALUATION OF FATIGUE IN
DISTANCE RUNNING

BY

Sharon Ann Evans

Chairperson: Dr. V. Dianne Ulibarri

The purpose of this study was to examine the process of fatigue in distance runners. Five trained, male runners comprised the sample for this study. Initially, each subject participated in a continuous, incremental treadmill run to exhaustion. Expired gases were collected and analyzed for oxygen and carbon dioxide concentrations. The purpose of this treadmill run was to obtain values of the ventilatory equivalent for oxygen uptake ($\dot{V}E/\dot{V}O_2$). The $\dot{V}E/\dot{V}O_2$ values obtained from this test were plotted against treadmill velocity. The points where the slope of the graph changed were labeled ventilatory breakpoint 1 and ventilatory breakpoint 2, respectively. Treadmill velocities corresponding to the ventilatory breakpoints were then determined. Velocities of 0.13m/sec above and below each breakpoint were calculated for each subject.

Each subject ran four, thirty minute, constant velocity runs (A, 1B, 2B, C) at their predetermined velocities. Standard cinematographic techniques were utilized to obtain film data from the

four runs. Filming occurred periodically throughout all runs. Data reduction occurred via digitization.

Segmental kinetic energy measures were calculated and utilized in multivariate analysis of covariance procedures to evaluate changes in bilateral kinetic energy measures of the thigh and shank at left foot strike, left midstance, left toeoff, right foot strike, right midstance and right toeoff. Findings included that while controlling for velocity, differences occurred between runs and also between trials within the runs. As a runner fatigued, there was an initial decrease in the magnitudes of the bilateral thigh and shank kinetic energies followed by erratic increases and decreases in kinetic energy values especially during the later trials in the 2B and C runs. More variability in kinetic energy values was evident in the swing phase than the support phase. The variability in the swing phase may be due to each runner's attempt to maintain running at the constant treadmill velocity as each subject fatigued. In conclusion, the changes found in kinetic energy values was indicative of inefficient movements due to the onset of fatigue.

DEDICATION

To my Mom and Dad

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CHAPTER I

INTRODUCTION

Fatigue is a complex phenomenon involving physiological, neuromuscular and psychological factors. Fatigue has been defined as a decrease in the capacity to do work caused by the act of performing work (Knuttgen, 1961). The effect fatigue has on repeated performances of gross motor skills is to produce irregularities in the internal timing of each performance (Bartlett, 1953). This study examined the process of fatigue in distance runners from a biomechanical and physiological perspective.

Statement of the problem

Physiologically, fatigue may result from: the depletion of the energy stores of the body, the accumulation of the waste products of metabolism, and from dehydration or electrolyte depletion (Sparks, 1975). In endurance activities, such as distance running, a gradual shift from aerobic to anaerobic metabolism is indicative of the onset of fatigue. The concentration of lactate in the blood is an indicator of the balance between lactate production and lactate clearance. A shift toward anaerobic metabolism is evidenced by an increase in the blood lactate concentration. The increase in lactic acid reduces the muscles' abilities to generate power and may also increase the energy cost of running by affecting the neuromuscular coordination or by causing changes in the contractability of the muscles by increasing the viscosity of the muscle (Henry, 1951; Margaria, Ceretelli, Aghemo & Sassi, 1963).

A related response to fatigue is an increase in pulmonary ventilation. This response is evidenced by an abrupt change in magnitude of the ventilatory equivalent for oxygen uptake. These physiological changes may affect the biomechanical aspects of the performance.

Biomechanically, the effects of fatigue on distance running performance are evidenced by a decrease in the velocity at which the runner can perform, a decrease in stride length and a decrease in stride rate. Changes in other kinematic factors are also evident. A confounding problem in evaluating changes in biomechanical parameters as a runner fatigues, is that it is difficult to isolate the changes in the pattern of running that are independent of the decrease in the velocity of the run.

Segmental kinetic energy analyses have been shown to be useful in detecting differences in skill analysis. Segmental kinetic energy measures have been shown to be good predictors of skill level (Evans, 1982; Garrett, 1970; Ulibarri, 1981). The fatigued runner exhibits movement patterns that are characteristic of less efficient (less skilled) runners. Therefore, in an attempt to understand the process

of fatigue in distance runners, it was the purpose of this study to address the following research questions:

1. Are there significant differences in bilateral kinetic energy patterns of the thigh and shank as a runner fatigues if the velocity of the run is held constant?

2. Are there significant differences in bilateral kinetic energy patterns of the thigh and shank at velocities that correspond to changes in the ventilatory equivalent for oxygen uptake from an incremental exercise test if the effects of velocity differences are controlled?

Need for the study

During endurance activities, slow twitch oxidative muscle fibers are recruited in the working muscles and the chemical energy for performance is provided through aerobic metabolism (deVries, 1986). As the slow twitch oxidative fibers begin to fatigue, fast twitch oxidative glycolytic and fast twitch glycolytic fibers are recruited in the working muscles to maintain the force production necessary to continue the activity. The recruitment of the fast twitch muscle fibers necessitates a switch from aerobic to anaerobic metabolism.

One of the by products of glycolysis is lactate (Astrand & Rodahl, 1986). Lactic acid is buffered by the bicarbonate system. The hydrogen ion derived from the production of lactic acid is responsible for the formation of carbonic acid which dissociates to form carbon dioxide and water (Davis, 1985). The increase in carbon dioxide stimulates the ventilatory control centers to increase ventilation to get rid of the excess carbon dioxide. The increase in ventilation is evidenced by a sharp rise in the ventilatory equivalent for oxygen uptake.

Changes in the kinematics and temporal aspects of running have been found when comparing running patterns in fatigued and nonfatigued states. These changes include a decrease in running velocity, decrease in stride length, decrease in stride rate, decreased time of support and nonsupport, and changes in body segmental positions.

A confounding problem in evaluating the effect of fatigue on running performance is the effect of change in running velocity as a runner fatigues. Segmental kinetic energy analyses have been shown to be useful in detecting differences in skill levels (Evans, 1982; Garrett, 1970; Ulibarri, 1981). Changes in segmental kinetic energy patterns have been shown to occur developmentally (Garrett, 1970; Mersereau, 1974, 1977) and patterns of kinetic energy measures have also been shown to be good predictors of skill level (Evans, 1982; Ulibarri, 1981). Bates, Osternig and James (1977) stated that fatigue in running is not only characterized by a general decrease in mechanical performance parameters, but also changes the relationship of biomechanical parameters involved in running. Therefore, since investigators utilizing kinetic energy analyses have determined that differences exist between skill levels, it was of interest to see whether the process of fatigue could be more clearly defined by utilizing a segmental kinetic energy analysis. By examining the process of changes in the patterns of intersegmental kinetic energy measures across time, changes due to fatigue may be detected. Therefore, the purpose of this study was to examine the process of the change in segmental kinetic energy measures within running patterns as the result of fatigue for five, trained male runners.

Hypotheses

H_a: There are significant differences in bilateral kinetic energy measures of the thigh and shank as a runner fatigues when the velocity of the run is held constant.

H_a: There are significant differences in bilateral kinetic energy measures of the thigh and shank in the selected constant velocities that coincide with changes in the ventilatory equivalent for oxygen uptake.

Limitations

1. Due to the lack of instrumentation sensitivity, fine differences in performance may not be detected.
2. The generalizability of the study was limited due to the following factors:
    a. The running velocities were different between subjects and different within a subject for the four constant velocity runs.
    b. Only subjects that were classified as trained male runners were used in this study. Beginning and elite levels and female runners may not produce similar results.
    c. Only one stride was analyzed for each selected filming within each constant velocity run.

Significance

The significance of the study was to provide insights into the process of change in running mechanics of trained runners as the result of physiological fatigue. By analyzing changes in running mechanics relative to physiological parameters, implications for training runners may become evident. Although the generalizability of the study was limited, the knowledge gained by utilizing a segmental kinetic energy analysis in the investigation of fatigue in running may provide insight into this complex process.

Definition of terms

1. Foot strike. The first frame of film in which the foot was in contact with the supporting surface.
2. Fast twitch glycolytic muscle fibers. Muscle fiber type characterized by a high glycogen content, a high concentration of lactate dehydrogenase, a short time to peak tension and a high degree of fatigueability. This muscle fiber type is innervated by large neurons that are stimulated by increased force demands.
3. Fast twitch oxidative gylcolytic muscle fibers. Muscle fiber type characterized by a moderate glycogen content, a short time to peak tension, a moderate degree of fatigueability and a high capillary density. This muscle fiber type has characteristics of both fast twitch glycolytic and slow twitch muscle fiber types.
4. Midstance. The frame of film in which the shank was perpendicular to the supporting surface.
5. Slow twitch oxidative muscle fibers. Muscle fibers characterized by a high concentration and larger mitochondria, a greater capillary density and a high lipid content. This muscle fiber type is innervated by small motorneurons that are easily excited.
6. Toeoff. The first frame of film in which the foot was no longer in contact with the supporting surface.
7. Ventilitory breakpoint 1. The point on the graph of the ventilatory equivalent of oxygen uptake vs treadmill velocity

where the slope changed without a concomitant increase in the ventilatory equivalent of carbon dioxide.

8. Ventilatory breakpoint 2. The point on the graph of the ventilatory equivalent for oxygen uptake vs treadmill velocity where the slope changed, coinciding with a simultaneous increase in the ventilatory equivalent for carbon dioxide.

CHAPTER II

REVIEW OF RELATED LITERATURE

The literature reviewed in this chapter was divided into two broad sections. The first section examined biomechanical aspects of the skilled pattern in running. Since this study examined the motion of the thigh and shank segments, the review was limited to the biomechanical aspects of lower extremity function. The second section examined selected metabolic responses during exercise.

Biomechanics of running

The biomechanics of the skilled pattern in running was discussed in this section. The biomechanical parameters have been categorized into three sections: temporal, kinematic and kinetic. Temporal aspects of running were also defined. As the focus of the study was on the motion of the lower extremity, the literature reviewed was limited to leg function while running. The changes that occurred in selected temporal, kinematic and kinetic parameters as a result of an increase in the velocity of the run were discussed, as well as the issue of whether running on a treadmill simulates overground running. The data for the study utilized a motor driven treadmill, on which each subject performed four thirty minute runs at four different velocities.

Temporal aspects

In rhythmical movement patterns such as running, it is convenient to describe the motion by defining a cycle of movement. A movement cycle was defined by Dillman (1975) as the time period from the initial occurrence of an event to the reoccurrence of that same event. The basic unit for this movement cycle is the running cycle which is defined as the period of time from foot strike of one foot until foot strike occurs again on the same foot (Dillman, 1975; Slocum & James, 1968). A stride is defined as the sequence of events that occurs from foot strike on one foot to foot strike on the opposite foot (Dillman, 1975; Slocum & James, 1968). The stride can also be designated as a right or left stride depending on which leg is defined as the leading leg.

Each stride can be divided further into two phases: support and nonsupport phases. The support or drive phase begins at foot strike and is terminated at toeoff (Dillman, 1975; James & Brubaker, 1973; Slocum & James, 1968). The nonsupport or recovery phase begins at toeoff of one foot and is terminated at foot strike of the same foot (Dillman, 1975; Slocum & James, 1968).

The support phase is further divided into three phases: foot strike, midsupport and toeoff (Slocum & James, 1968). Foot strike begins when the foot first contacts the running surface and continues until the foot becomes firmly fixed to this surface. The midsupport phase starts once the foot is firmly fixed and continues until the heel begins to rise off the surface. Toeoff begins when the heel starts to rise off the running surface and continues until the toes leave the ground.

The nonsupport phase is also divided into three phases: followthrough, forward swing and foot descent (Slocum & James, 1968). The followthrough phase begins as the trailing foot leaves the running surface and continues until deceleration of the extremity is complete and forward swing begins. The forward swing phase of the leg is initiated as the thigh begins to move forward in the sagittal plane and terminates when maximum flexion of the hip is reached. The foot descent phase begins when maximum flexion of the hip is completed and continues until foot strike (James & Brubaker, 1973; Slocum & James, 1968).

As the velocity of the run increases, the total time for a running cycle decreases (Hoshikawa, Matsui & Miyashita, 1973; James & Brubaker, 1973; Saito, Kobayashi, Miyashita & Hoshikawa, 1974). By dividing the cycle time into the two components of support and nonsupport time, researchers (Bates & Haven, 1974; Bates, Osternig & Mason, 1978; Chapman & Caldwell, 1983; Elliott & Roberts, 1980; Frishberg, 1983; Hoshikawa, Matsui & Miyashita, 1973; James & Brubaker, 1973; Luhtanen & Komi, 1978; Nelson, Dillman, Lagasse & Bickett, 1972; Nelson & Gregor, 1976; Nelson & Osterhoudt, 1971; Yoneda, Adrian, Walker & Dobie, 1979) reported that both the absolute and relative time spent in the support phase decreased as the velocity of the run increased. Relative support time decreased from

approximately 68 percent of the cycle time at 3.35 m/s (Nelson, Dillman, Lagasse & Bickett, 1972) to 54 percent of the cycle time at 6.4 m/s (Nelson, Dillman, Lagasse & Bickett, 1972) to 47 percent of the cycle time at 9.2 m/s (Frishberg, 1983).

Changes in relative nonsupport time were the inverse of changes occurring in relative support time. However, changes in absolute nonsupport times were found to be inconsistent when examined across a range of velocities. Increases in nonsupport time coincided with increases in running velocity when patterns of running at velocities ranging from 2.5 to 6.4 m/s were studied (Elliott & Blanksby, 1976; Nelson, Dillman, Lagasse & Bickett, 1972). Other researchers (Luhtanen & Komi, 1978; Nelson & Gregor, 1976; Nelson & Osterhoudt, 1971) indicated small differences in nonsupport time as the velocity of the run increased, with the longest nonsupport times occurring at intermediate speeds.

Kinematics

The support phase begins with foot strike. The supporting extremity has four functions during the time it is in contact with the running surface: (1) to absorb the impact at foot strike, (2) to support the body's weight, (3) to maintain forward movement of the body and (4) to accelerate the body's center of mass against internal and external resistances (Elliott & Blanksby, 1979; James & Brubaker, 1973; Slocum & James, 1968). As the foot contacted the running surface, the initial force of impact was absorbed by the foot and the ankle and knee joints (Dyson, 1962; James & Brubaker, 1973). When running overground at a constant velocity, the supporting extremity contacted the surface slightly ahead of the vertical projection of the body's center of mass (Dyson, 1962; Hay, 1985; James & Brubaker, 1973) and at or near zero velocity relative to the ground (Hay, 1985; James & Brubaker, 1973). Placement of the foot in this manner minimized the braking action caused by the vertical ground reaction force (James & Brubaker, 1973). At foot strike, the tibia was perpendicular to the ground and the knee was flexed at approximately 30 to 40 degrees.

These researchers further stated that as the lower extremity moved into midsupport, the hip became adducted slightly. The knee did not change position appreciably when moving from foot strike to midsupport.

As the supporting extremity moved into the takeoff phase of support, the foot remained fixed, the pelvis moved backward with the trailing leg and the hip extended and internally rotated. The knee began extension and the ankle plantar flexed which increased leg length (James & Brubaker, 1973; Slocum & James, 1968). The supporting extremity rolled forward over the ball of the foot to the point where the toes were about to leave the supporting surface. Force was provided by the forward inclination of the lower extremity and extension of the lumbar joints, hip, knee and ankle (James & Brubaker, 1973; Slocum & James, 1968).

In the recovery phase, the followthrough period began as the trailing foot left the supporting surface. To accomplish this phase, the direction of the recovery leg had to be reversed. Reversal occurred as the recovery extremity made the transition between the followthrough to the forward swing phase (James & Brubaker, 1973). During this period of nonsupport, the decelerating leg moved backward. This leg movement placed the foot at its farthest point behind the vertical projection of the body's center of mass.

During the forward swing period, the movement of the thigh was rapid and was accompanied by knee flexion. The amount of knee flexion increased with increases in the velocity of the run (James & Brubaker, 1973). A rapid forward swing of the recovery leg increased the push off of the supporting extremity, and therefore, maximized the forward movement of the body (James & Brubaker, 1973). The knee reached its maximal flexion position after the thigh passed the center of mass of the body. Knee flexion was primarily a passive movement (James & Brubaker, 1973; Slocum & James, 1968) and served two functions. First, knee flexion shortened the length of the leg so that the foot could clear the ground. Secondly, decreasing the length of the lower extremity raised the segment's center of mass and therefore reduced the amount of angular inertia of the limb so that the thigh could accelerate to a velocity that exceeded the velocity of the body's center of mass. The knee remained in this flexed position until the hip approached full flexion. The thigh continued in its forward motion but began to decelerate and the knee began extending so that at the time hip flexion was completed, the extension of the knee placed the shank in a position which was nearly perpendicular to the supporting surface. A factor that was found to limit a runner's ability to run at faster velocities was how quickly the recovery extremity could be moved forward in preparation for the next foot strike without excessive braking action (James & Brubaker, 1973).

In the early part of forward leg swing the body was airborne. The body remained in this nonsupport state until the forward movement of the recovery thigh reached a position just posterior to the body's center of mass. At this point, foot strike occurred on the opposite leg (Dyson, 1962; Slocum & James, 1968). The period of support on the opposite leg continued until the hip reached its maximum flexion position. At this point toeoff of the opposite leg occurred and the body was again in a state of nonsupport (James & Brubaker, 1973; Slocum & James, 1968).

The period of foot descent began after hip flexion was completed and continued until foot strike. After maximum hip flexion, the swinging thigh moved backward and the knee continued extending. Knee extension was aided by the transfer of angular momentum from the thigh (James & Brubaker, 1973). The forward movement of the leg and foot were decelerated to zero velocity. The knee was in a position of approximately 30 degrees of flexion. The foot was now at its farthest position anterior to the body (Slocum & James, 1968) and needed only to be positioned for contact. The entire lower extremity moved backward through the action of the hip and lumbar joints during positioning of the foot. At the time of foot strike, the lower limb was moving backward at a velocity that was equal to the forward velocity of the runner (Slocum & James, 1968).

Stride length and stride rate. Stride length (SL) is defined as the horizontal displacement traversed from the initial contact of one foot to the initial contact of the opposite foot (Williams, 1985a). Stride time (ST) is defined as the time period between the initial contact of one foot and the initial contact of the opposite foot, and stride rate (SR) is the reciprocal of stride time (Williams).

Stride length has been divided into the horizontal displacement covered during both the support and nonsupport times. These displacements have been termed support and nonsupport lengths (Dillman, 1975; Williams, 1985a).

Stride length and running velocity. As the velocity of the run increased (from 3.5 to 6.5 m/s), the length of the stride has been shown to increase linearly for overground running (Buchanan, 1971; Osterhoudt, 1968; Saito, Kobayashi, Miyashita & Hoshikawa, 1974). Hogberg (1952) and Hoshikawa, Matsui and Miyashita (1973) found a similar relationship between stride length and velocity of the run in a study of running on a treadmill. Several studies also confirmed the linear relationship between stride length and running velocity for this range of velocities (Hoshikawa, Miyashita & Matsui, 1971; Matsui, Miyashita & Miura, 1970; Murase, Kamei, Hoshikawa, Miyashita & Matsui, 1972).

At velocities greater than 6.5 m/s, stride lengths have also been reported to increase (Dittmer, 1962; Hogberg, 1952; Hoshikawa, Matsui & Miyashita, 1973; Nelson & Osterhoudt, 1971; Rapp, 1963; Sinning & Forsyth, 1970; Teeple, 1968), although the relationship between stride length and velocity of running was unclear. At maximal running velocities, stride length has been shown to decrease slightly when running in both overground (Saito, Kobayashi, Miyashita & Hoshikawa, 1974) and treadmill situations (Hogberg, 1952; Matsui, Miyashita & Miura, 1970).

Comparisons among different skill levels in running have indicated that the more skilled runners had a greater stride length for a given velocity than less skilled runners. This trend was noted for both overground (Deshon & Nelson, 1964; Dittmer, 1962; Fenn, 1930; Saito, Kobayashi, Miyashita & Hoshikawa, 1974) and treadmill (Cavanagh, Pollock & Landa, 1977; Hogberg, 1952; Hoshikawa, Miyashita & Matsui, 1971; Hubbard, 1939; Matsui, Miyashita & Miura, 1970; Murase, Kamei, Hoshikawa, Miyashita & Matsui, 1972) running. One investigation yielded results that were contrary to this general trend. In a longitudinal study of running, Nelson and Gregor (1976) noted that stride length decreased. They concluded that since the performance times of the runners improved over the course of the study, a decrease in stride length for a given velocity was indicative of a more skillful performance. One study (Ulibarri, 1974), found no difference in stride length due to homogeneity of groups and training.

Stride rate and running velocity. Stride rate has been shown to increase in a curvilinear manner as the velocity of the run increased (Buchanan, 1971; Hoshikawa, Matsui & Miyashita, 1973; Osterhoudt, 1968; Saito, Kobayashi, Miyashita & Hoshikawa, 1974). For velocities ranging from 3 to 6 m/s, relatively small increases were noted in stride rate. As the velocity of the run is increased to greater that 6 m/s, greater increases are noted in the frequency of the stride. These results have been shown to occur for both overground (Teeple, 1968) and treadmill running (Hogberg, 1952; Hoshikawa, Matsui & Miyashita, 1973; Hoshikawa, Miyashita & Matsui, 1971; Matsui, Miyashita & Miura, 1970; Murase, Kamei, Hoshikawa, Miyashita & Matsui, 1972; Sinning & Forsyth, 1970). Comparisons of skilled with less skilled runners indicated that the skilled runners had a lower stride rate for a given velocity (Hoshikawa, Miyashita & Matsui, 1971; Murase, Kamei, Hoshikawa, Miyashita & Matsui, 1972; Saito, Kobayashi, Miyashita & Hoshikawa, 1974). In conclusion, at lower velocities stride length increased to a greater extent than stride rate in order that running velocity could be increased. At higher velocities, stride rate increased to a greater extent as compared to stride length to compensate for the increase in running velocity (Hoshikawa, Matsui & Miyashita, 1973).

Segmental positions. The angle of the thigh from the vertical at foot strike has been shown to range from 20.8 degrees at 3.4 m/s (Elliott & Blanksby, 1979) to 28.9 degrees at 9.2 m/s (Frishberg, 1983) for treadmill running. The angle of the thigh at foot strike has shown little variation at velocities greater than 4 m/s (Cavanagh, Pollock & Landa, 1977; Clarke, Cooper, Clarke & Hamill, 1985; Dillman, 1971; Elliott & Ackland, 1981; Elliott & Blanksby, 1979; Frishberg, 1983; Williams, 1980). Thigh angles ranged from 30 degrees at 5.0 m/s (Cavanagh, Pollock & Landa, 1977) to 28.9 degrees at 9.2 m/s (Frishberg, 1983).

As the supporting extremity moved into the toe off phase, thigh angles have been shown to range from 24.0 degrees at 3.57 m/s (Williams, 1980) to -29.0 to -32.0 degrees at velocities of 8 to 9 m/s (Dillman, 1971; Frishberg, 1983). Negative values indicated hip extension. The hip has been reported to continue extending several degrees after toe off (Dillman, 1971; Elliott & Ackland, 1981; Elliott & Blanksby, 1979; Williams, 1980).

During the nonsupport phase, maximal thigh angles were reported to occur prior to foot strike. As the velocity of the run increased, hip flexion increased (Cavanagh, Pollock & Landa, 1977; Dillman, 1971; Elliott & Ackland, 1981; Elliott & Blanksby, 1979; Elliott & Roberts, 1980; Sinning & Forsyth, 1970). The trend of increased hip flexion with increased velocity was noted for both overground (Dillman, 1971) and treadmill running (Elliott & Blanksby, 1979; Cavanagh, Pollock & Landa, 1977).

The angle of the knee, measured from a line extending from the thigh, at foot strike has been reported to range from 21 to 30 degrees (Bates, Osternig & Mason, 1978; Clarke, Cooper, Clarke & Hamill, 1985; Clarke, Frederick & Cooper, 1983; Dillman, 1971; Elliott & Blanksby, 1979; Elliott & Roberts, 1980). The angle of the knee during the support phase has been shown to range from 38 to 50 degrees for running velocities ranging from 3.4 to 7.5 m/s (Bates, Osternig & Mason, 1978, 1979; Bates, Osternig, Mason & James, 1979; Cavanagh, Pollock & Landa, 1977). No trend was noted for the knee angle at foot strike or during support as running velocity increased.

Williams (1985a) hypothesized that the position of the lower leg at initial ground contact may affect the changes that occur in the horizontal velocity of the body which occur during contact. The position of the rear of the foot at the initial point of contact is approximately 22 to 26 cm horizontally anterior to the hip. This displacement has been reported to decrease slightly as the velocity of the run increased (Bates, Osternig & Mason, 1978, 1979; Cavanagh, Pollock & Landa, 1977; Giradin & Roy, 1978). The angle of the lower leg from the vertical at foot strike has been reported to range from eight to eleven degrees at running velocities from 3.4 to 4.5 m/s (Bates, Osternig & Mason, 1978; Yoneda, Adrian, Walker & Dobie, 1979). As the velocity of the run increased, this angle of the lower leg measured from the vertical approached zero degrees (Bates, Osternig & Mason, 1979; Dillman, 1971; Frishberg, 1983). Bates, Osternig and Mason (1979) examined the relationship between the angle of the lower leg with the ground at foot strike and the decrease in the horizontal velocity of the body during the support phase. They concluded that there was no relationship between these two parameters.

At toe off, the knee was found not to be completely extended. Knee angle measures have been reported to range from 27.3 degrees at a running velocity of 2.5 m/s (Elliott & Blanksby, 1979) to 18 degrees at a running velocity of 8.0 m/s. Greater extension as velocity increased was found to occur (Bates, Osternig & Mason, 1978; Cavanagh, Pollock & Landa, 1977; Dillman, 1971; Elliott & Blanksby, 1979).

During the period of nonsupport, angles of maximal knee flexion increased with increased velocity (Cavanagh, Pollock & Landa, 1977; Dillman, 1971; Grillner, Halbertsma, Nilsson & Thorstensson, 1979; Sinning & Forsyth, 1970; Williams, 1980). As stated earlier, greater knee flexion during the swing phase decreased the moment of inertia of the entire lower extremity about the hip joint and therefore decreased the amount of resistance to hip flexion (Cavanagh, Pollock & Landa, 1977; Dillamn, 1971; Grillner, Halbertsma, Nilsson & Thorstensson, 1979; Williams, 1980). Maximal knee extension has been reported to occur prior to foot strike with slight flexion of a few degrees occurring just prior to ground contact by the foot (Bates, Osternig & Mason, 1978; Williams, 1980).

Segmental velocities. At foot strike, the lower extremity was found to move backward relative to the hip (Dillman, 1974). The velocity of the foot has been reported to be approximately 1.0 to 1.4 m/s prior to foot strike for running velocities ranging from 3.5 to 4.5 m/s. Foot velocities have been shown to have the same magnitudes for both treadmill (Clarke, Cooper, Clarke & Hamill, 1985) and overground running (Cavanagh, 1982; Cavanagh, Valiant & Misevich, 1983). An analysis of the components of the velocity of the foot at contact indicated that the horizontal component was slightly higher (0.9 to 1.3 m/s) when compared to the vertical component (0.55 to 0.75 m/s). Cavanagh (1982) reported that the vertical component of velocity had a wider variability between subjects than the horizontal component of velocity for a given velocity.

Kinetics

The kinetic analysis employed in this study focused on the kinetic energy output of the upper and lower leg segments for both legs. Studies that have utilized a segmental kinetic energy approach to skill analysis will be reviewed as kinetic energy has been shown to be a good predictor of skill performance. Finally, studies that have utilized a kinetic energy analysis to evaluate running performance will be discussed.

Kinetic energy and skill analysis. The energy of an object by virtue of its motion is termed its kinetic energy (Beer & Johnston, 1988). Kinetic energy patterns for body segments have been shown to be discriminating parameters for skill performance. In a longitudinal study, Garrett (1970) analyzed the jumping pattern of a male subject at two, three and four years of age. Changes were noted in the kinetic energy patterns as the child developed. Observable changes were greater magnitude of the total body kinetic energy and greater magnitudes in the kinetic energy of individual body segments.

The running patterns of female infants at 22 and 25 months of age were studied by Mersereau (1974). Developmental trends were noted in the kinetic energy patterns for the segments of the lower right extremity, the total body kinetic energy, the instantaneous horizontal component of the body's center of mass, stride length and the nonsupport time.

In 1977, Mersereau examined the running and jumping patterns of female children from three to five years of age. Utilizing a multiple regression statistical analysis, selected kinetic energy measures were found to be good predictors of the velocity of the run and moderate predictors of jumping distance.

The kinetic energy patterns of female softball batters were examined by Ulibarri (1981). Subjects were divided into skilled and unskilled batters based on skill level. Using vision scores and kinetic energy values of the bat as dependent variables and strength measures as the covariate in a multiple regression statistical analysis, the kinetic energy values were found to be good predictors of skill level. Ulibarri (1981) noted a more consistent pattern of kinetic energy of the bat for the skilled batters when compared to the unskilled batters. The consistency in the kinetic energy patterns of the bat was suggested as representing a more effective summation of forces by the skilled softball batters.

Evans (1982) utilized segmental kinetic energy measures to analyze differences between skilled and unskilled throwers. Kinetic energy measures for the upper arm, forearm and hand of the throwing arm, the values of kinetic energy for the forearm were found to be the best predictor of skill level.

In summary, these studies suggest that a segmental kinetic energy analysis is a useful tool for skill analysis. Developmental trends have been observed and differences between levels of skill also have been found.

<u>Kinetic energy in running</u>. One of the earliest investigators to utilize a kinetic energy analysis to evaluate the running pattern was Fenn (1930). In the examination of the kinetic energy curves of the thigh and shank, Fenn noted that as the foot was positioned for foot strike the kinetic energy of the thigh increased slightly until the foot made contact with the ground. At foot strike, the kinetic energy of the thigh decreased slightly. The kinetic energy of the thigh again increased until the entire leg reached a position near the end of the support phase, where it subsequently decreased. During the recovery phase, the kinetic energy of the thigh again increased as the leg reached the end of its backward movement. As

the entire leg moved forward, the kinetic energy of the thigh also increased.

Fenn (1930) reported that the kinetic energy values of the shank had three distinct peak values. The kinetic energy of the shank approached a minimal value just prior to foot strike. At the point of foot contact with the ground, the kinetic energy of the shank increased and reached its first peak value toward the end of the support phase. As the thigh initiated its forward movement, the kinetic energy of the shank decreased and approached a minimal value. As the knee flexed in the recovery phase, the kinetic energy of the shank increased and reached its second peak value. As knee extension began, the shank kinetic energy decreased. At the point of maximal hip flexion, knee extension accelerated which was depicted as the third peak value in the graph of the kinetic energy of the shank.

Three peaks in the kinetic energy values of the shank were also reported by Cavagna, Saibene and Margaria (1964). One peak value was found after foot strike. The magnitude of this peak increased with increasing velocity of the runner. The peak in shank kinetic energy occurred simultaneously with a similar peak in the thigh of the same leg. It was concluded that this kinetic energy pattern of the thigh and shank represented the result of the ground reaction force in the support phase.

Overground versus treadmill running

An important issue that must be addressed when analyzing the running pattern using a treadmill is how the accuracy that running on a treadmill simulates a runner's overground running pattern. A number of authors analyzed these two modes of running have found conflicting results. Dal Monte, Fucci and Manoni (1973) examined the running patterns of three trained middle distance runners. Each subject had 24 weeks of treadmill running (30 hours) prior to being filmed. The subjects ran at velocities of 15, 18 and 20 km/hr for both the treadmill and the overground conditions. They concluded that the vertical displacement of the body on the treadmill was less than running overground. They also noted that the forward swing, foot descent and the stride were shorter on the treadmill. In addition they found that the observed differences between the two modes of running diminished with increases in the velocity of the run.

A comparison of three different velocities (3.35, 4.88 and 6.40 m/sec) and three different slopes (horizontal, 10% uphill and 10% downhill) for both treadmill and overground running was conducted by Nelson, Dillman, Lagasse and Bickett (1972). Subjects had six training sessions to become accustomed to treadmill running. In an analysis of the temporal factors of support and nonsupport times, a significant increase ($p<.01$) in support time for treadmill running was noted for the horizontal slope at 6.40 m/sec, at all three velocities for the 10% uphill slope ($p<.05$) and at 4.88 m/sec and 6.40 m/sec for the 10% downhill slope ($p<.05$). In the comparison of nonsupport time, significant decreases ($p<.01$) for treadmill running were noted for the 10% uphill condition at velocities of 3.55 and 4.88 m/sec. Significant increases ($p<.01$) in stride length for treadmill running and significant decreases ($p<.01$) in stride rate for treadmill running were observed at 6.40 m/sec for both the horizontal and the 10% uphill conditions. An analysis of mean vertical velocities yielded results which were significantly greater ($p<.01$) for the overground condition.

An evaluation of male and female running patterns between overground and treadmill running was conducted by Elliott and Blanksby (1976). Two velocities were selected for the males (3.97 and 5.29 m/sec) and two velocities for the female subjects (3.70 and 5.41 m/sec). Speeds were selected from the self selected speeds by the subjects in overground running. Subjects had ten training sessions on the treadmill to become adapted to treadmill running. No significant differences were noted for the slower velocities for either males or females on the selected variables. For the faster velocities, however, significant decreases were observed on the treadmill for the time of nonsupport. They concluded that at velocities greater than 5 m/sec variations in running technique were evident.

Frishberg (1983) compared the running patterns for overground and treadmill conditions for a mean velocity of 9.21 m/sec. No significant differences ($p<.05$) were noted for support and nonsupport times, stride length or stride frequency. A comparison of joint angles yielded differences ($p<.05$) in the support phase. When compared to running on a treadmill, a greater shank angle at foot strike was observed in the overground condition, while a greater thigh angle at foot strike was found for the treadmill running when compared with overground running.

In conclusion, when significant differences were noted between overground and treadmill running modes, the significant differences generally occurred at velocities greater than 5 m/sec. For velocities greater than 5 m/sec, results of running on a treadmill compared to overground running indicated a variety of differences for the following parameters: increased stride length and decreased stride rate (Nelson, Dillman, Lagasse & Bickett, 1972), decreased stride length and increased stride rate (Elliott & Blanksby, 1976), increased support time (Nelson, Dillman, Lagasse & Bickett, 1972), decreased nonsupport time (Elliott & Blanksby, 1976), and less variability and lower vertical velocities of the body's center of mass (Nelson, Dillman, Lagasse & Bickett, 1972). Therefore, it was difficult to conclude if treadmill and overground running patterns differ.

Biomechanical indices of fatigue in running

In an investigation of fatigue in distance running, Elliott and Ackland (1981) examined changes in selected kinematic parameters in subjects at selected times throughout a 10 km race. Subjects were filmed at the 780 m, 3980 m, 6780 m and 9580 m marks of the race. Significant decreases ($p<.05$) were noted for the velocity of the run as the runners fatigued. Examining the stride length and rate to determine which of these factors decreased to cause the decrease in the velocity of the run, a significant decrease ($p<.05$) was observed for stride length as the runners fatigued. Variations in stride rate were not significant. Examination of selected parameters at foot strike yielded a significant quadratic trend ($p<.05$) for the horizontal distance of the ankle to the vertical projection of the body's center of mass. The relative backward velocity of the ankle at foot strike decreased ($p<.05$) as the runners fatigued.

Elliott and Ackland (1981) examined the position of the trunk, thigh and shank at selected phases throughout the running cycle. Significant differences ($p<.05$) were noted in the foot strike phase. The trunk and shank segments displayed a significant quadratic trend. A significant linear trend was noted for the thigh segment. In the recovery phase, a significant linear trend ($p<.05$) was determined for the recovery shank when the recovery thigh was perpendicular to the ground.

An evaluation of fatigue in middle distance runners was conducted by Elliott and Roberts (1980). Subjects were filmed at the 500 m, 1300 m, 2100 m and 2900 m marks of a 3000 m time trial. An attempt was made to regulate velocity by placing markers every 100 m on a 400 m track. Subjects were instructed to be at these points on the track in synchrony with an auditory signal. An examination of the parameters of support and nonsupport time and stride length and rate yielded no significant differences across the four data collection sessions. An examination of angular positions of the trunk, thigh, shank and foot yielded significant differences for the shank at foot strike ($p<.05$), at maximum thigh hyperextension during recovery ($p<.05$) and at maximum thigh flexion during recovery ($p<.10$). Significant differences were also noted for the hip angle at maximum thigh hyperextension during recovery ($p<.10$) and at maximum thigh flexion during recovery ($p<.05$). No significant differences were noted for the angular velocity of the thigh, shank and foot at selected points in the running cycle.

Adrian and Kreighbaum (1973) investigated changes in foot placement, angles of the lower extremity and asymmetrical movement patterns in subjects performing in a 24-hour relay in which each subject ran 27-31 miles in one mile intervals. Filming occurred at miles 10-12 and at miles 28-30. Results indicated that no definitive pattern emerged for changes in thigh and shank angles. Asymmetry was also found. They concluded that there were individual adjustment variations between filming trials and asymmetrical patterns were found for most runners.

The effects of fatigue in running a 400 m run were examined by Bates, Osternig and James (1977). Subjects were filmed at the 169 m and 370 m mark. A temporal analysis indicated that significant differences ($p<.05$) occurred for the total time of support for both legs when comparing the fatigued state to the nonfatigued state and the time for the foot strike plus midsupport phase for the left leg. The time of nonsupport was significantly different ($p<.05$) for both legs. Between the fatigued and the fatigued states in the recovery phase, significant differences ($p<.05$) were noted for the time of nonsupport for both legs. Significant increases ($p<.05$) in time were noted for the foot strike and foot descent phases for both legs as the runner fatigued and a significant decrease ($p<.05$) in time for the forward swing phase of both legs. An analysis of selected velocity parameters indicated significant decreases ($p<.05$) in velocity for support and nonsupport phases of both legs. Stride length decreased significantly from the nonfatigued to the fatigued state.

An examination of segmental angles at selected points in the running cycle indicated significant increases ($p<.05$) for the right thigh at right heel lift, and left takeoff and touchdown. Significant increases ($p<.05$) for the left thigh occurred at the point of right end of followthrough, right touchdown and left heel lift. Significant increases ($p<.05$) for the right shank occurred at the point of right end of forward swing and heel lift and significant decreases ($p<.05$) at the point of left end of forward swing and left touchdown. Significant increases ($p<.05$) for the left shank occurred at the point of right end of followthrough and left end of forward swing and left heel lift and significant decreases ($p<.05$) occurred at the point of right end of forward swing, right touchdown and right heel lift. Significant decreases ($p<.05$) in trunk position occurred at the point of right end of followthrough, right end of forward swing and right touchdown, and left takeoff and left end of followthrough. Bates, Osternig and James (1977) concluded that fatigue in running did not produce consistent uniform reductions in the components of the running pattern but changed the relationship between the components.

An investigation into fatigue in distance running under three different conditions was conducted by Williams, Snow and Arguss (1988). They examined the changes in selected kinematic parameters in intercollegiate competition, a non-competitive maximal track run and a constant velocity treadmill run. In an attempt to control for velocity differences, regression equations were generated for each subject from data collected at four velocities of nonfatigued running. Comparisons of the nonfatigued to the fatigued state yielded significant increases ($p<.05$) in stride length for the non-competitive and treadmill conditions. Other significant differences ($p<.05$) were increased maximal knee flexion angle during nonsupport for the treadmill condition and an increased maximal thigh angle (measured from the vertical) during hip flexion in the competitive run condition. They concluded that running while fatigued did not result in dramatic changes in the kinematic parameters investigated when looking at group means, but changes within individuals were more pronounced. This conclusion indicated that subjects had individual adaptations to fatigue.

A similar conclusion was reached by Chapman (1982) in a study investigating the effects of fatigue on sprint running. The total range of motion of the thigh and knee decreased as the subjects fatigued. No pattern emerged to explain the decrease in range of motion. Chapman (1982) suggested that segmental energy transfers in the lower extremities may play a role in subjects' adaptation to fatigue.

A study investigating kinematic and kinetic effects of fatigue on the mechanics of sprint running was conducted by Sprague and Mann (1983). Subjects were filmed at the 40 m mark of a 50 m maximal exertion sprint. A force platform was also utilized to record kinetic data simultaneously with the cinematographic data. A second phase of data collection was performed in which subjects were filmed at the 40 m and 380 m marks of a 400 m run. The force platform was not utilized in the longer run since the investigators felt that the subjects might have to alter their running pattern in order to strike the platform. The acceleration of the body's center of mass was utilized to determine the ground force components. An examination of the selected temporal and kinematic parameters indicated significant decreases ($p<.05$) in stride rate and in the horizontal velocity of the body's center of mass. Significant increases ($p<.05$) were found for the support time, the loss in horizontal velocity of the body's center of mass and the foot horizontal velocity prior to foot strike. The kinetic parameter examined was joint muscle moment. Significant differences ($p<.05$) were found in the integrated moment about the hip during both the extensor and flexor dominant portion of the support phase. In relating these differences to the decrease in the horizontal velocity of the body center of mass, Sprague and Mann (1983) found an inverse relationship between the joint moment about the hip during the extensor dominant portion of the support phase and the decrease in the horizontal velocity of the body center of mass. The kinematic parameters found to be related to this change were the change in the displacement of the hip at foot strike, the change in displacement of the body center of mass at foot strike and the change in hip angle at the point where the moment about the hip was zero.

During the flexors dominant portion of the support phase, there was a direct relationship between the joint moment and the decrease in the horizontal velocity of the body center of mass. The change in hip angle at the point where the joint moment was equal to zero was found to be significantly related to the direct relationship between the joint moment at the hip and the decrease in the horizontal velocity of the body center of mass.

The joint moment at the knee displayed a significant inverse relationship to the change in the horizontal velocity of the body center of mass during the flexors dominant portion of the support phase. The significantly related kinematic variables were determined to be the change in displacement of the body center of mass at foot strike, the change in hip angle at maximum flexion and the change in knee angle at foot strike.

A significant direct relationship was found between the joint moment at the knee and the decrease in the horizontal velocity of the body center of mass during the extensors dominant portion of the support phase. The change of the ankle angle at the point where the moment about the knee was equal to zero and the change in hip angle at toeoff were the kinematic variables significantly related. Sprague and Mann (1983) concluded that the change in selected parameters did not lie in the inability of the subjects to produce the joint moments, but in the subjects inability to coordinate the joint moment production with the onset of fatigue.

In summary, several studies (Bates, Osternig & James, 1977; Chapman, 1982; Elliott & Ackland, 1981; Sprague & Mann, 1983) have noted a significant decrease in the velocity of the run when comparisons were made between fatigued and nonfatigued running. It was difficult when interpreting the results of these studies to determine which changes in the biomechanical parameters were independent of the decrease in the velocity of the run. In addition, several researchers (Bates, Osternig & James, 1977; Chapman, 1982; Williams, Snow & Agruss, 1988) have suggested that the responses elicited in the fatigued state were individualized. When the changes were examined on an individual subject basis, dramatic changes were evident. When the subjects were grouped and means were examined for selected parameters, differences were often masked due to the individual adaptations to fatigue. Sprague and Mann (1983) concluded that changes in selected biomechanical parameters between fatigued and nonfatigued running were due to the inability to coordinate segmental motions rather than the inability to produce force.

Physiological indices of fatigue

In non-steady state exercise, there are several measures that can be used as indicators of anaerobic metabolism: (a) an increase in blood lactic acid, (b) a decrease in blood pH and bicarbonate (c) an increase in the respiratory exchange ratio (RER) due to increased carbon dioxide, and (d) a deviation from linearity in the slope of the ventilatory equivalent of oxygen uptake ($\dot{V}E/\dot{V}O_2$) (Wasserman & McIllroy, 1964). The mechanisms that elicit these responses will be discussed in this section.

Muscle fibers within a given muscle are recruited according to the work intensity demand. At low work intensity levels, slow twitch oxidative fibers are recruited and lipids serve as the primary energy source. As the work intensity level increases, fast twitch fibers are recruited to meet the increased demand. In prolonged exercise at low or moderate work intensity levels, the slow twitch oxidative fibers will eventually become fatigued. To continue working at the same intensity level, fast twitch fibers are recruited (Davis, Frank, Whipp & Wasserman, 1979; deVries, 1986). As mentioned earlier, fast twitch fibers utilize glycogen or glucose as their primary energy source. Energy is provided through glycolysis which is the sequence of reactions that converts glycogen into pyruvate. After glycolysis, the sequence of reactions in the citric acid cycle and the electron transport chain harvest most of the energy contained in glucose.

As the intensity of exercise increases, the rate of pyruvate production by glycolysis exceeds the rate of its oxidation by the citric acid cycle. Pyruvate is then converted to lactate by lactic dehydrogenase (Brooks, 1985; Styer, 1981).

Plasma lactate

The lactate produced in working muscle can follow one of several pathways. Some of the lactate diffuses into adjacent muscle fibers where it is metabolized. Brooks and Fahey (1986) have proposed the Lactic Acid Shuttle hypothesis to explain the balance of production and removal of lactic acid during exercise. Lactate that does not diffuse into muscle tissue diffuses or is transported out of the muscle and enters the bloodstream (Essen, Pernow, Gollnick & Saltin, 1971). The lactic acid that enters the plasma or extracellular fluid is buffered by the bicarbonate system as follows:

lactic acid + sodium bicarbonate -> sodium lactate + carbonic acid

The hydrogen ion derived from the production of lactic acid is responsible for the formation of carbonic acid which dissociates to form carbon dioxide and water (Davis, 1985). The concept of ventilatory breakpoints is related to these chemical reactions. The increase in ventilation has been shown to be associated with carbon dioxide production and therefore has been used as an indicator of lactate production.

Determination of ventilatory breakpoints

The method used for the determination of ventilatory breakpoints involves examination of the graph of the ventilatory equivalent for oxygen uptake ($\dot{V}E/\dot{V}O_2$) versus work intensity. The point at which the pulmonary ventilation ($\dot{V}E$) increases disproportionately to the increase in oxygen uptake ($\dot{V}O_2$) is evidenced by a change in slope of the VE/VO_2 graph. The point at which there is an increase in the ventilatory equivalent for oxygen uptake ($\dot{V}E/\dot{V}O_2$) without a concomitant increase in $\dot{V}E/\dot{V}CO_2$ has been termed the first ventilatory breakpoint. In incremental exercise tests there is often a second point in the curve of $\dot{V}E/\dot{V}O_2$ where the slope again changes. This second change in slope of the $VE/\dot{V}O_2$ graph is accompanied by a change in the slope of the $\dot{V}E/\dot{V}CO_2$ graph. This point has been termed the second ventilatory breakpoint or the respiratory compensation threshold (Simon, Young, Gutin, Blood & Case, 1983). In incremental exercise tests, the rise in $\dot{V}E/\dot{V}CO_2$ has been shown to denote the end of isocapnic buffering and the onset of hypocapnia (Hagberg, Mullin & Nagle, 1978; Hughson & Green, 1982; Simon, Young, Gutin, Blood & Case, 1983).

Increase in carbon dioxide production

At normal muscle pH, the lactate produced is dissociated and buffered by the bicarbonate system (Wasserman, Van Kessel & Burton, 1967). Hydrogen ions enter the blood plasma and extracellular fluid which initiates the formation of carbon dioxide by the following reaction:

$$H+ + HCO- \rightarrow H2CO3 \rightarrow CO2 + H2O.$$

The buffering of lactic acid causes an increase in the partial pressure of carbon dioxide (PCO2) and the hydrogen ion concentration of the venus capillary blood. Therefore, the increase in carbon dioxide is not caused by an increase in lactate ions in the blood, but by the increase in hydrogen ions (Davis, 1985; James & Ehrsam, 1982). The ventilatory control mechanisms are stimulated to maintain homeostasis of $PaCO_2$ and hydrogen ions. The increased concentration of carbon dioxide and hydrogen ions cause the ventilation to increase to return the system to equilibrium. Jones and Ehrsam (1982) concluded that of all the factors that influence the slope of the $\dot{V}E/\dot{V}O_2$ graph, the most significant is the sharp increase in arterial carbon dioxide due to the hydrogen ion efflux from muscle.

Biomechanical-metabolic relationships

Hogberg (1952) and Knuttgen (1961) investigated the effects of altered stride length on oxygen uptake. A subject ran at a freely chosen stride length, and at 17 percent of leg length above and below the freely chosen stride length (Hogberg, 1952). The shorter stride length resulted in an increase of six percent in oxygen uptake and the longer stride length resulted in a 12 percent increase in oxygen uptake when compared to the oxygen uptake of the freely chosen stride length. Hogberg (1952) concluded that the freely chosen stride length was the most economical length, evidenced by the resulting oxygen uptake measures. Knuttgen (1961) found similar results in examining several velocities and variations from the freely chosen stride length.

Cavanagh and Williams (1982) compared the effects of altered stride length on oxygen uptake. The freely chosen stride length was compared with stride lengths of 6.7, 13.4 and 20 percent of leg length above and below the freely chosen stride length. They concluded that small changes in stride length did not have a significant effect on the oxygen uptake. Their results conflicted with Hogberg (1952) in that the effects of shorter or longer stride lengths on oxygen uptake varied among individual subjects.

The authors of these studies concluded that for a given velocity, there is an optimum stride length for each individual such that increases or decreases in this length resulted in increases in metabolic energy expenditure (oxygen uptake) (Cavanagh & Kram, 1985). Furthermore, runners selected stride lengths that were close to their optimum stride lengths.

The results of these studies indicate that stride length is an important biomechanical parameter in determining efficient running patterns. However, it is difficult to isolate the effects of a single parameter. By altering the length of the stride, other kinematic and kinetic parameters also become altered (Williams, 1985b). Therefore, it is difficult to identify a causative relationship for the effects of altered stride length on oxygen uptake.

Williams and Cavanagh (1987) investigated relationships between distance running mechanics, selected physiological parameters and performance time. Subjects were classified into three groups based on their submaximal oxygen uptake while running at the test velocity. Three dimensional kinematic and kinetic data were determined for both overground and treadmill running. In addition, kinetic data was collected by use of a force platform for overground running. Williams and Cavanagh (1987) included a large number of kinematic and kinetic variables in their initial analysis. A factor analysis was used to select a smaller number of variables to be used in subsequent analyses. This analysis yielded ten factors; the variables with the highest loading for each factor were retained for subsequent analyses. The variables were shank angle at foot strike, thigh angle at foot strike, net positive power, step length as a percentage of leg length, maximal plantar flexion angle, total mechanical power, thigh angle at toeoff, net impulse in the mediolateral direction, wrist excursion and vertical impulse. A multiple regression analysis was performed using submaximal oxygen uptake as the dependent variable. Three variables which accounted for 54 percent of the variance were shank angle at foot strike, maximal plantar flexion angle and net positive power. Variables that were significantly different ($p<.05$) between the groups were the magnitude of the first peak in the vertical ground reaction force, angle of the shank with the vertical at foot strike, maximum plantar flexion angle, forward trunk lean, minimum velocity of the knee joint center during the support phase and the energy transfer between the legs and trunk. Williams and Cavanagh (1987) concluded that mechanical parameters of technique in running influenced metabolic energy costs. They further concluded that relationships existed between mechanical and metabolic variables during distance running. No single biomechanical factor was thought responsible for differences in submaximal oxygen uptake between the groups, but a combination of biomechanical factors tended to differentiate the groups.

In conclusion, studies that have investigated relationships between biomechanical and metabolic factors in distance runners have indicated that runners tend to adopt a stride length that is physiologically economical (Cavanagh & Williams, 1982; Hogberg, 1952; Knuttgen, 1961) and that a combination of biomechanical parameters was necessary for distinguishing between submaximal oxygen uptake differences when running at constant velocities (Williams & Cavanagh, 1987).

CHAPTER III

METHODOLOGY

The purpose of this study was to examine the process of fatigue in distance runners. To examine the process of fatigue, two separate analyses were conducted. First, the changes in selected kinetic parameters of the lower extremities were examined as each subject fatigued while running at four different constant velocities. The four velocities for each runner were determined from the results of a continuous, incremental treadmill run to exhaustion. The four velocities for each runner were determined from the curve of the ventilatory equivalent of oxygen uptake versus treadmill velocity graph. The second analysis examined the changes in selected kinetic parameters of the lower extremities that occurred across the four constant velocity runs for each subject while controlling for the differences in treadmill velocities.

The procedures for the collection and analysis of both the biomechanical and physiological data are described in this chapter. The procedures for the collection and analysis of the physiological data will be discussed first since the biomechanical analyses were based on the physiological results of a maximal treadmill run to exhaustion. Data collection was conducted over a three week period so as to minimize any training effect. The sampling and cinematographic methods utilized in this study were consistent with current biomechanical techniques. Typically, studies involving cinematographic techniques have employed small sample sizes due to the amount of time required for data reduction from film. Energy metabolism procedures utilized in this study were consistent with current physiological research techniques.

Sampling

Five trained male distance runners, ranging in age from 20 to 40 years, comprised the sample used in this study. Each subject was informed as to the nature of the study and was asked to sign an informed consent form prior to being allowed to participate in the study. A copy of the informed consent form will be found in the Appendix.

The subjects selected to participate in this study were trained treadmill runners. Each subject had just completed a three month training period in which they ran on a motor driven treadmill two days per week at various treadmill velocities. Expired gases were collected and analyzed and heart rate response was recorded throughout each run. Subjects were accustomed to performing while being attached to equipment necessary to collect these physiological data.

Energy metabolism procedures

Each subject participated in a continuous, incremental treadmill run to exhaustion. Expired gases were collected and analyzed continuously throughout this run for each subject, and heartrate response was recorded. In addition, 20 ul blood samples were taken before and after the run to determine lactate levels. From the results of the maximal treadmill run, four velocities were determined for each runner. Each runner participated in four, thirty minute constant velocity runs. Expired gases were collected and analyzed continuously and heartrate response was recorded throughtout each thirty minute constant velocity run for each subject. Three 20 ul blood samples were taken for each run. The procedures for the collection of the physiological data for this study will be discussed in this section.

Maximal treadmill run

Initially, each subject participated in a continuous, incremental treadmill run to exhaustion in order to obtain $\dot{V}E/\dot{V}O_2$ values from which ventilatory breakpoints could be calculated. The maximal run began with the treadmill velocity set at 2.28 meters per second (m/sec). At the end of each minute, the treadmill velocity was increased 0.13 m/sec. The treadmill grade remained at 0% throughout the test. Resting values for heartrate and blood pressure were determined prior to the treadmill run. Prior to the test, a 20 ul arterialized blood sample was drawn from a finger on the prewarmed left hand of each subject for the determination of a resting blood lactate measure. Subjects' weights were recorded before the test. The electrocardiogram was monitored prior to and throughout the treadmill run using an electrocardiographic recording of the CM-5 lead. Heartrate response was recorded continuously throughout the test, by recording the number of heart beats per bag time of expired gas.

Gas analysis

Expired gas was collected at approximately thirty second intervals in neoprene weather balloons. Oxygen uptake was determined by the open-circuit Douglas bag method. Subjects inspired through a two-way Daniels respiratory valve which was connected to a four-way automated switching valve by 0.61 meters of corregated tubing (3.175 cm I. D.).

Gas analyzers were calibrated prior to the start of each treadmill run. Helium was used to zero the analyzers. A standard gas sample, verfied for carbon dioxide and oxygen concentrations with a Haldane chemical analyzer, was then used to calibrate the analyzers. Expired gases were analyzed for percentages of carbon dioxide and oxygen using an infrared carbon dioxide analyzer (Applied Electrochemistry CD-3A) and an electrochemical oxygen analyzer (Applied Electrochemistry S-3A). Gas volumes were determined using a DTM-115 dry gas meter. Gas was analyzed at a constant rate of 50 liters per minute.

The work capacity variables of minute pulmonary ventilation ($\dot{V}E$), oxygen uptake ($\dot{V}O_2$), ventilatory equivalent for oxygen uptake ($\dot{V}E/\dot{V}O_2$) and respiratory exchange ratio (RER) were calculated using the equations of Consolazio, Johnson and Pecora (1963). The test was terminated by the subject at the point of exhaustion. After test termination, two minutes of expired gases were collected in thirty second intervals and were analyzed. At the end of the two minute recovery period, a 20 ul blood sample was obtained and analyzed to determine a posttest blood lactate measure.

Blood lactate analysis

The 20 ul blood samples were transferred to haemolysis tubes which were treated with ethylenedinitrilo tetraacetic acid tripotassium salt (EDTA-K3) and cetrimid ($CH_3(CH_2)_{15}N(CH_3)_3Br$). The blood samples were then buffered with a diluting solution composed of Sodium Phosphate Dibasic ($Na_2HPO_4 \cdot H_2O$), Sodium Phosphate Monobasic ($Na_2H_2PO_4 \cdot H_2O$) and Sodium Azide (NaN_3) dissolved in double distilled water. The buffered samples were analyzed using a Roche Bio-Electronics Lactate Analyzer 640 for the determination of a blood lactate measure.

Determination of ventilatory breakpoints

Values of $\dot{V}E/\dot{V}O_2$ obtained from the maximal treadmill run were smoothed and plotted against treadmill velocity. Ventilatory breakpoints were determined by a group of eight investigators working independently. Ventilatory breakpoint 1 was defined as the point at which the slope of the $\dot{V}E/\dot{V}O_2$ curve changed. Ventilatory breakpoint 2 was defined as the point in the plot of the $\dot{V}E/\dot{V}O_2$ curve where the slope again changed. The treadmill velocities that coincided with the two ventilatory breakpoints were determined. Out of the eight velocities for each breakpoint, the extreme high and low values were discarded. The remaining six values had a range of 0.0 to 0.09 m/s for four of the subjects. One subject had a range of 0.27 m/s for the second breakpoint. The mean of the remaining six values for each breakpoint was used to determine the ventilatory breakpoints.

After the ventilatory breakpoints were established, treadmill velocities of 0.13 m/sec above and below each breakpoint were determined. These velocities were then used as the four, thirty minute constant velocity treadmill runs which were performed by each subject for this study. Runs at the treadmill velocities above and below the first ventilatory breakpoint were labeled A and 1B respectively. Runs at the treadmill velocities above and below the second ventilatory breakpoint were labeled 2B and C respectively (see Figure 1). Randomization of run order was performed to minimize any training effect.

Thirty minute, constant velocity runs

The following protocol was used for each of the four thirty minute treadmill runs. Resting measures of blood pressure, heartrate and blood lactate were obtained prior to each test. Subjects ran at a treadmill velocity of 2.68 m/sec for five minutes as a warmup. A

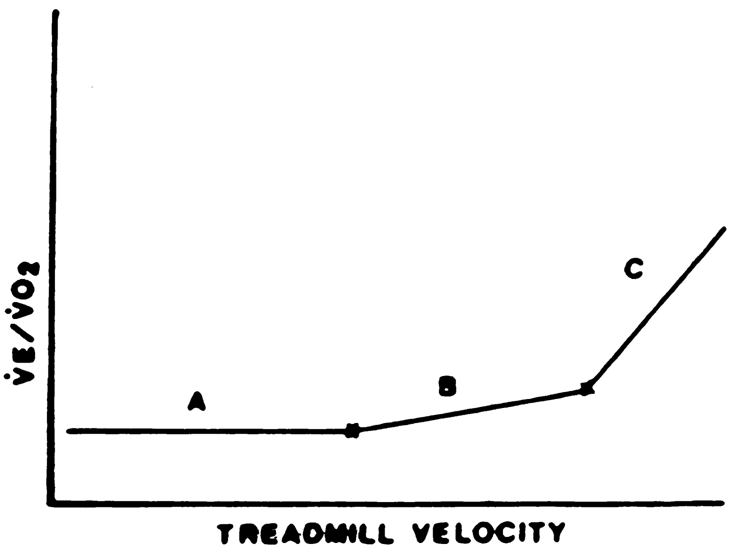

Figure 1. Ventilatory breakpoints

20 ul arterialized blood sample was obtained immediately after the warm-up period for the determination of a post warmup blood lactate measure. The treadmill velocity was increased to one of the four predetermined velocities for each runner. Subjects performed on the treadmill at the predetermined velocity for a thirty minute period or until voluntary termination due to exhaustion. Expired gases were collected and analyzed and heartrate response was recorded continuously throughout each run, using procedures identical to the continuous, incremental treadmill run. Work capacity measures of minute pulmonary ventilation ($\dot{V}E$), oxygen uptake ($\dot{V}O_2$), ventilatory equivalent of oxygen uptake ($\dot{V}E/\dot{V}O_2$) and respiratory exchange ratio (RER) were calculated. A 20 ul blood sample was collected immediately after the run terminated for the determination of blood lactate.

Cinematographic procedures

High speed cinematography was utilized at selected time intervals throughout the thirty minute constant velocity runs to obtain the biomechanical data for this study. Two 16mm high speed cameras were used which provided sagittal and frontal views of the performance. Standard cinematographic procedures used in this study will be discussed in this section.

Subject preparation

Black cotton targets used as joint markers were applied with rubber cement to the lateral aspect of the left shoulder, elbow, wrist, hip, knee and ankle joint centers, and on the medial aspect of the right elbow, wrist, knee and ankle joint centers of the subjects for each 30 minute run. In addition, targets were placed on the tips of the running shoes. The targets were used to aid in the location of joint position coordinates in the data reduction phase of the study. Subjects wore the same pair of running shoes for each of the four data collection sessions.

Filming setup

Two 16mm LOCAM high speed cameras were utilized to obtain the film data for this study. Kodak 4-X Reversal 16mm film was used in both cameras. One camera, placed perpendicular to the plane of motion, provided a sagittal view of the performance. This was the primary camera used for the cinematographic analysis. The frame rate was set at 100 frames per second (fps) with a shutter angle of 120 degrees which allowed an exposure rate of 1/300 second. The second camera was placed perpendicular to the primary camera and in front of the subject to provide a frontal view of the performance. The frame rate was set at 50 fps with a shutter angle of 120 degrees which allowed an exposure rate of 1/150 second. The purpose of this second camera was to allow qualitative evaluation of motion out of the sagittal plane. Timing lights were placed in the fields of view of both cameras to validate film speed. Meter sticks were filmed in the field of view of each camera prior to data collection. Each meter stick provided a linear multiplier standard for the conversion of film displacements to actual displacements for their respective camera. The treadmill belt was marked with a piece of adhesive tape for validation of treadmill velocity from the film.

Filming protocol

Five filmings trials were performed for the A and 1B runs. For these runs, the subjects were filmed at 5:30, 11:30, 17:30, 23:30 and 29:30 minutes into the run. For the 2B and C runs, filming occurred more frequently at 2:30, 5:30, 8:30, 11:30, 14:30, 17:30, 20:30, 23:30, 26:30 and 29:30 minutes into the run. Additional filming trials were selected for the treadmill runs associated with the second breakpoint because it was believed that the subjects would fatigue sooner while running at higher velocities. If a subject was unable to complete a given run, filming occurred when the subject indicated he was fatigued. Approximately five strides were recorded during each filming trial for each of the four thirty minute runs for each subject.

Anthropometric measurements

Heights of ankle, knee and hip joints were measured using anthropometers. The lateral malleolus, lateral epicondyle and greater trochanter of both legs were used as anatomical reference points. The heights were obtained by measuring from the floor to the center of the black cotton targets. These measures were used to compare leg lengths as symmetry between legs was not assumed.

Data reduction

The film was digitized using an ALTEK rear projection system in conjunction with an IBM PC. The second left stride of each data set for each subject was chosen for digitization. Seventeen joint position coordinates were entered for each frame of data. The sequence of entered points was as follows: left toe, left ankle, left knee, left hip, right hip, right knee, right ankle, right toe, left fingertips, left wrist, left elbow, left shoulder, right shoulder, right elbow, right wrist, right fingertips and the top of the head (see Figure 2). The points of left foot strike (LFS), left midstance (LMS), left toeoff (LTO), right foot strike (RFS), right midstance (RMS) and right toeoff (RTO) were determined and recorded in the digitization process.

Data smoothing

Finite difference methods based on the Taylor expansions series were utilized for calculating the first derivative function. The first central difference formula was utilized for calculating velocity:

$$x_i' = \frac{x_{i+1} - x_{i-1}}{2(dt)} \qquad (1)$$

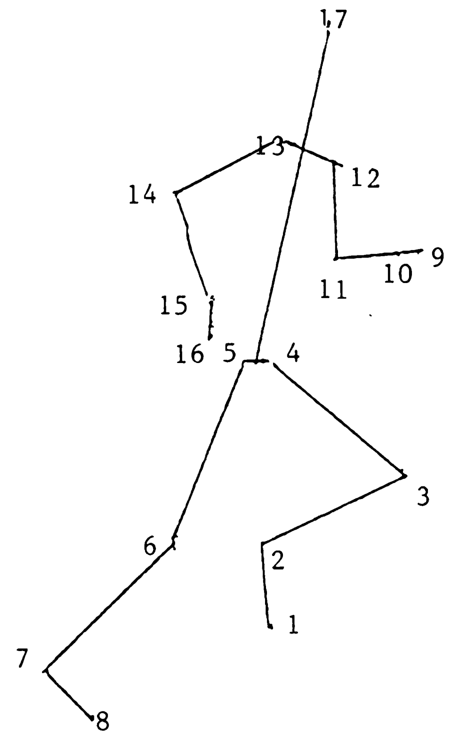

Figure 2. Joint coordinate points

where x_i = specific point

x_{i+1} = point to the right of x_i

x_{i-1} = point to the left of x_i

dt = the time interval between two points.

The first forward difference was used for the first point:

$$x_i' = \frac{x_{i+1} - x_i}{(dt)} \qquad (2)$$

and the first backward difference was utilized for the last point:

$$x_i' = \frac{x_i - x_{i-1}}{(dt)} \qquad (3)$$

This procedure resulted in the loss of two data points; one frame at each end of the data set.

Data analyses

The techniques used to analyze both the biomechanical and physiological data will be discussed in this section. The segmental kinetic energy patterns of the shank and thigh segments comprised the kinetic analysis for this study.

Physiological parameters that were examined were oxygen uptake ($\dot{V}O_2$), ventilatory equivalent for oxygen uptake ($\dot{V}E/\dot{V}O_2$), respiratory exchange ratio (RER), heartrate and blood lactate. The physiological measures were utilized in two manners. First, these measures were used to quantify the effect of physiological fatigue. Secondly, the physiological parameters were examined in relation to selected biomechanical parameters.

Kinetic analysis

A FORTRAN program was utilized to calculate the total kinetic energy for each body segment. Segmental masses were determined utilizing body segmental weighting factors based on the cadaver studies of Dempster (1955). Segmental moments of inertia were also calculated based on Dempster's work. Total segmental kinetic energy measures were determined by summing the translational and rotational kinetic energy values for each body segment.

Physiological data analysis

Expired gases were collected continuously throughout each of the four thirty minute constant velocity runs for each subject. The work capacity variables that were calculated from the expired gases were oxygen uptake ($\dot{V}O_2$), ventilatory equivalent of oxygen uptake ($\dot{V}E/\dot{V}O_2$) and respiratory exchange ratio (RER). In addition heart rate response was recorded continuously and 20 ul blood samples were collected before the five minute warmup period, immediately after the warmup period and two minutes after the run was terminated. The blood samples were analyzed for lactate concentration. The oxygen uptake ($\dot{V}O_2$), ventilatory equivalent of oxygen uptake ($\dot{V}E/\dot{V}O_2$) and the respiratory exchange ratio (RER) values were examined within each thirty minute run for each subject to evaluate the extent of physiological fatigue. These work capacity variables were examined in terms of their deviation from steady state work rate and in terms of the change from aerobic to anaerobic metabolism. The blood lactate measures were examined with the other metabolic measures to estimate the extent to which the subject was in anaerobic metabolism.

The oxygen uptake ($\dot{V}O_2$), ventilatory equivalent of oxygen uptake ($\dot{V}E/\dot{V}O_2$), respiratory exchange ratio (RER) and blood lactate measures were also examined across the four thirty minute runs for each subject to evaluate the physiological changes that occurred in relation to the two ventilatory breakpoints.

Statistical analysis

The statistical design used in this study was a 5 X 4 factorial, block by treatment design. The blocking factor in this design was subject, one subject for each block. The treatment factor had four levels corresponding to the four thirty minute constant velocity treadmill runs. Nested within each treatment were trials occurred at the predetermined times for the collection of the cinematographic data.

The purpose of this study was to examine the process of fatigue in distance runners. Two methods of analysis were selected to analyze this process. First, the changes in kinetic energy measures of the thigh and shank were examined while the velocity of the run was held constant. To examine changes in biomechanical parameters, a multivariate analysis of covariance analysis (SPSS-X, 1986) was performed utilizing bilateral kinetic energy values of the thigh and shank at the events of foot strike midstance and toeoff. Since the treadmill velocities between and within subjects for each of the four, thirty minute constant velocity treadmill runs were different, treadmill velocity was used as a covariate.

CHAPTER IV

RESULTS AND DISCUSSION

The purpose of this study was to examine the process of fatigue in distance runners. This process was examined in two ways. First, the changes in bilateral thigh and shank kinetic energy measures were examined as runners fatigued while running at constant velocities. Second, changes in bilateral kinetic energy measures were examined across four runs at velocities that corresponded to changes in the ventilatory equivalent for oxygen uptake.

The results of the analyses of this study were presented in the following order: physiological data analysis, statistical analysis and kinetic energy analysis. A discussion of the results is included in each of these sections.

Physiological data analysis

The collection of the physiological data for this study involved two phases. First, each subject performed an incremental, maximal treadmill run to exhaustion in order to obtain values for the ventilatory equivalent for oxygen uptake so that breakpoints could be determined. The second phase of the physiological data collection was based on the results obtained from the maximal treadmill test. The velocities of the four, thirty minute, constant velocity runs were determined from the graph of the ventilatory equivalent for oxygen uptake ($\dot{V}E/\dot{V}O_2$) obtained from the incremental, maximal treadmill run. The physiological parameters of oxygen uptake ($\dot{V}O_2$), $\dot{V}E/\dot{V}O_2$, respiratory exchange ratio (RER), heart rate and lactate were collected during the four, thirty minute constant velocity runs and were used as indicators of anaerobic metabolism. The results of the continuous, incremental maximal treadmill run and the physiological data from the four, thirty minute constant velocity runs will be discussed in this section.

Maximal treadmill run

Each subject participated in a continuous, incremental treadmill run to exhaustion in order to obtain values for the ventilatory equivalent for oxygen uptake ($\dot{V}E/\dot{V}O_2$) from which ventilatory breakpoints could be determined. These $\dot{V}E/\dot{V}O_2$ values obtained were smoothed and plotted against treadmill velocity. Breakpoints were calculated by determining changes in the slope of the $\dot{V}E/\dot{V}O_2$ graph. The velocities that corresponded to the changes in slope of the $\dot{V}E/\dot{V}O_2$ graph were determined and labeled ventilatory breakpoint 1 and ventilatory breakpoint 2 respectively. Velocities of 0.13 m/sec above and below each breakpoint were calculated. These four velocities were used for the A, 1B, 2B and C thirty minute, constant velocity runs. This procedure was used for each of the five subjects. The velocities for the two ventilatory breakpoints and the velocities for each of the thirty minute, constant velocity runs for each subject can be found in Table 1.

Thirty minute, constant velocity runs

The results of the physiological data for the thirty minute, constant velocity runs were similar for all subjects. Therefore, the data from one subject was presented. The work capacity measures of $\dot{V}O_2$, $\dot{V}E/\dot{V}O_2$, heart rate and RER for the A and 1B runs for subject 5 can be found in Figures 3a-d and 4a-d. No appreciable change in slope was noted in the graphs of any of the parameters. This pattern was consistent for the A and 1B runs for those subjects who completed the A and 1B runs (subjects 2, 3 and 5). However, for the subjects who were unable to complete the A and 1B runs (subjects 1 and 4), a slight increase in slope was seen in the $\dot{V}E/\dot{V}O_2$ graph. Therefore, these subjects were unable to maintain steady state. The physiological data for the 2B and C runs of subject 5 are displayed in Figures 5a-d and 6a-d. Examination of the slopes of the graphs of the 2B run (Figure 5a-d) indicated that no appreciable change in the slope of the graph occurred for VO_2, RER or heart rate. The graph of the VE/VO_2, however, did change at a constant slope throughout the run. Examination of the slopes of the graphs for the C run (Figure 6a-d) yielded a similar pattern as the 2B run. That is, no appreciable change in slope occurred for the $\dot{V}O_2$, RER or heart rate graphs. Examination of the $\dot{V}E/\dot{V}O_2$ graph of the C run indicated that the slope of the graph was greater than the slope of the graph of the

Table 1

Treadmill velocities (m/sec) for ventilatory breakpoints and constant velocity runs

Subject	Vent-brkpt1	Vent-Brkpt2	A	1B	2B	C
1	5.32	5.77	5.19	5.46	5.64	5.90
2	3.58	4.25	3.44	3.71	4.12	4.38
3	3.58	5.01	3.44	3.71	4.88	5.14
4	4.70	5.28	4.56	4.83	5.14	5.41
5	3.62	4.34	3.49	3.76	4.20	4.47

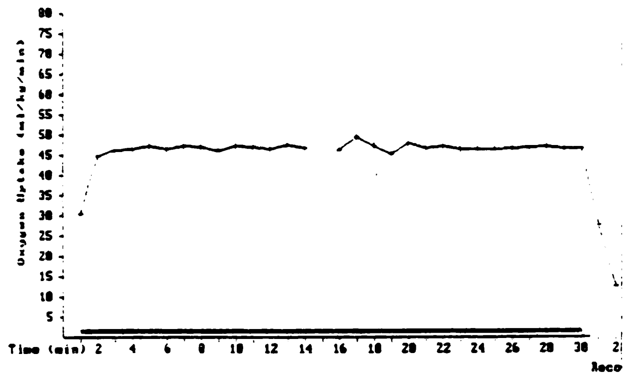

Figure 3a. Run A: $\dot{V}O_2$

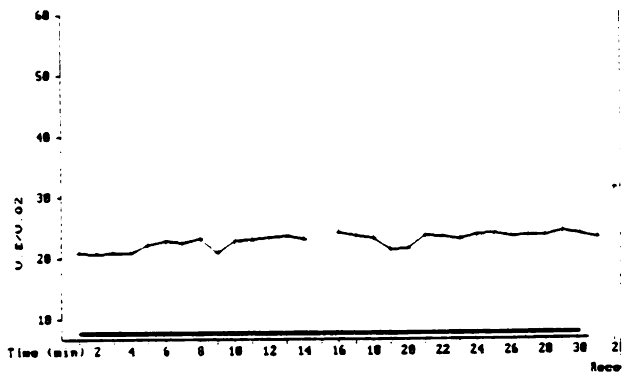

Figure 3b. Run A: $\dot{V}E/\dot{V}O_2$

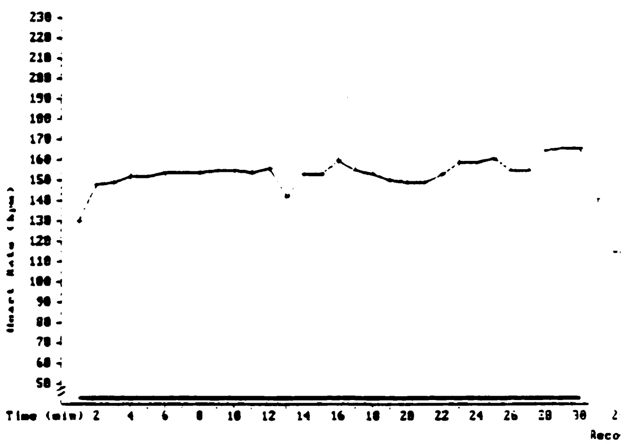

Figure 3c. Run A: Heart rate

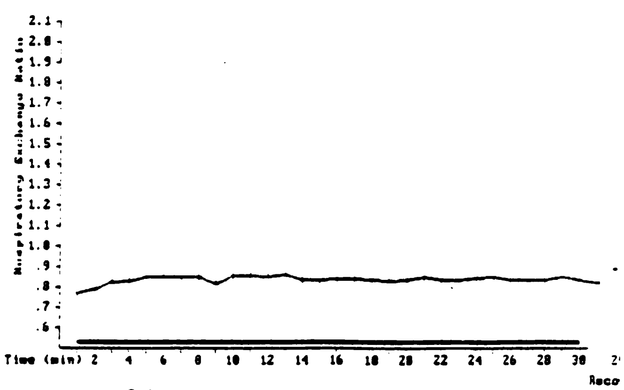

Figure 3d. Run A: RER

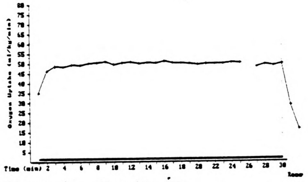

Figure 4a. Run 1B: $\dot{V}O_2$

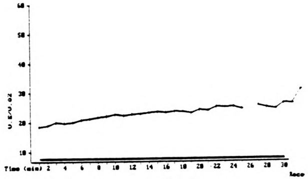

Figure 4b. Run 1B: $\dot{V}E/\dot{V}O_2$

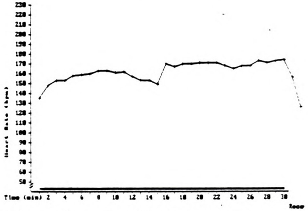

Figure 4c. Run 1B: Heart rate

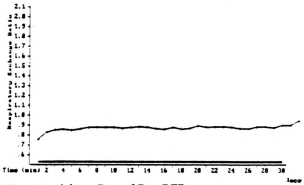

Figure 4d. Run 1B: RER

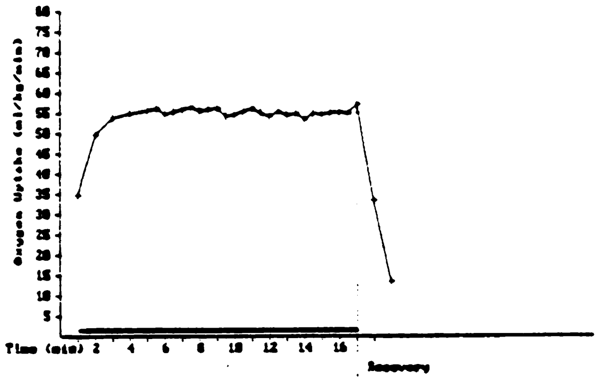

Figure 5a. Run 2B: $\dot{V}O_2$

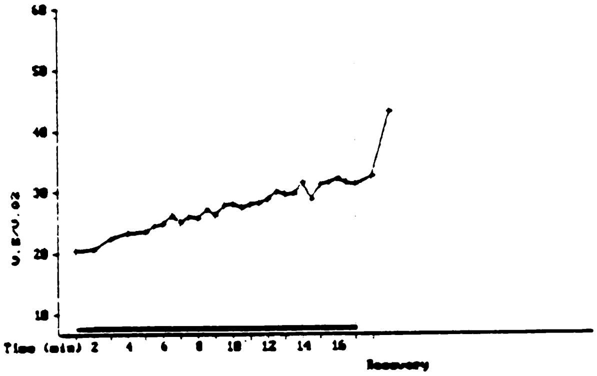

Figure 5b. Run 2B: $\dot{V}E/\dot{V}O_2$

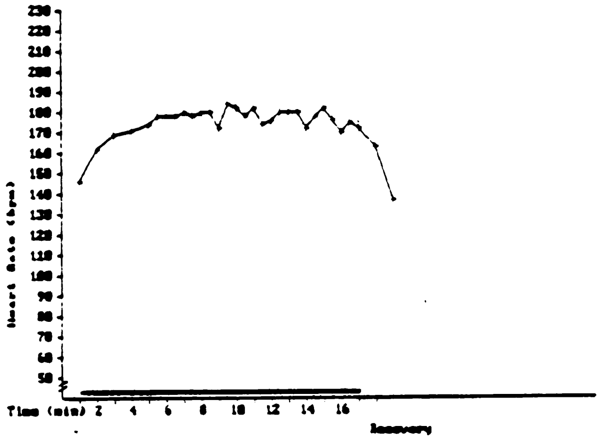

Figure 5c. Run 2B: Heart rate

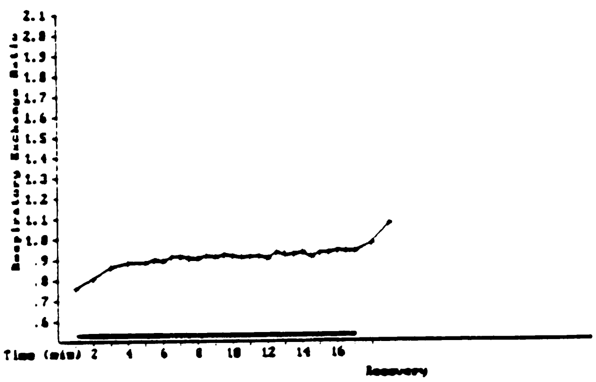

Figure 5d. Run 2B: RER

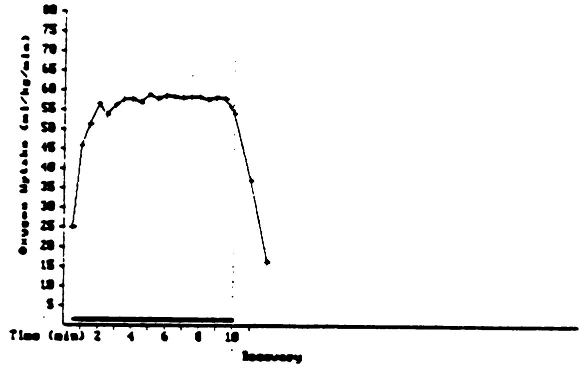

Figure 6a. Run C: $\dot{V}O_2$

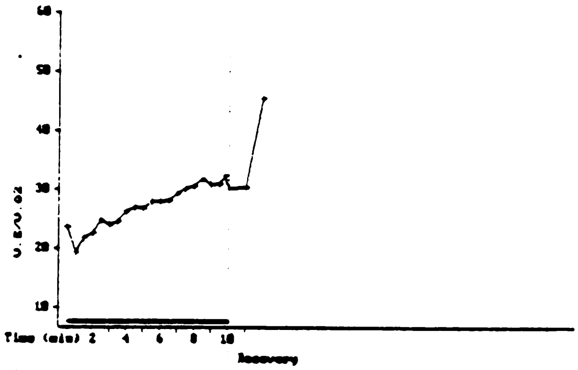

Figure 6b. Run C: $\dot{V}E/\dot{V}O_2$

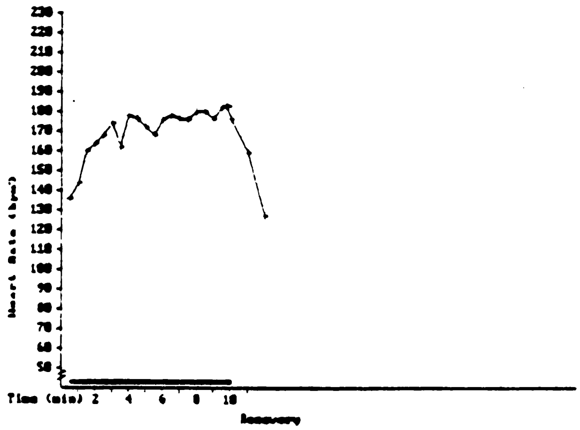

Figure 6c. Run C: Heart rate

Figure 6d. Run C: RER

VE/VO_2 graph for the 2B run. This greater slope indicated a higher intensity work rate for the C run. This pattern in the slopes of the graphs of the 2B and C runs was consistent across all subjects.

Examination of the blood lactate data for each of the four, thirty minute, constant velocity runs (Table 2) indicated that all subjects had a sharp increase in blood lactate in the 2B and C runs. Post run blood lactate levels exceeded 4 mmol/l for the two subjects that were unable to complete the A and 1B runs.

In summary, the inability of the subjects to maintain steady state was not reflected in the graphs of $\dot{V}O_2$, RER or heart rate. However, the change in ventilation reflected by the slope of the $\dot{V}E/\dot{V}O_2$ graph suggested that the subjects were not in steady state. Therefore, the most sensitive measure of the subjects' inability to maintain steady state was found to be the graph of the $\dot{V}E/\dot{V}O_2$.

Statistical analysis

The purpose of this study was to examine the process of fatigue in distance runners. Five trained male runners served as subjects in this study. Each subject performed four, thirty minute, constant velocity runs at predetermined velocities. A 5 X 4 multivariate analysis of covariance factorial design was utilized to analyze the data from this study. Subjects were used as blocking factors, one subject per block. The four, thirty minute, constant velocity runs were the treatments and nested within treatments were the five trials in which cinematographic data were collected. Treadmill velocity was used as a covariate to control for initial differences

Table 2

Blood lactate values (mmol/l) for constant velocity runs

	Subject	Resting	Post warm-up	Post run
Run A	1	1.65	1.40	10.20
	2	1.50	2.55	3.95
	3	1.50	1.35	1.65
	4	0.95	1.60	5.10
	5	0.90	2.10	1.80
Run 1B	1	2.00	1.45	9.90
	2	1.50	2.00	4.75
	3	1.60	1.80	1.70
	4	1.20	1.55	6.45
	5	0.95	2.25	3.90
Run 2B	1	1.15	1.60	11.75
	2	2.95	2.35	8.70
	3	2.15	1.70	10.20
	4	1.85	2.20	10.75
	5	1.45	1.15	7.00
Run C	1	1.50	1.60	11.80
	2	1.40	2.00	9.15
	3	1.45	1.10	9.50
	4	0.65	0.75	10.75
	5	1.05	1.95	8.95

in the velocities for the four, thirty minute, constant velocity runs.

The first hypothesis tested was that there were significant differences in bilateral kinetic energy measures of the thigh and shank as a runner fatigued when the velocity of the run was held constant. The second hypothesis tested in this study was that there were significant differences in bilateral kinetic energy measures of the thigh and shank in the selected constant velocities that coincided with changes in the ventilatory equivalent for oxygen uptake.

Four multivariate analysis of covariance analyses were performed to evaluate changes in kinetic energy measures of the right and left thigh and shank at selected points throughout the cycle of the run. The selected points were left foot strike (LFS), left midstance (LMS), left toe off (LTO), right foot strike (RFS), right midstance (RMS) and right toe off (RTO). The kinetic energy measures at these selected points in the cycle of the run served as the dependent variables for the four analyses. Three effects were tested in each analysis: main effect of subject, main effect of run and the effect of trial within run. A significant main effect for the blocking factor subject was expected since each subject occupied one block.

Two multivariate analysis of covariance analyses were performed to evaluate changes in selected kinetic energy measures between the right and left sides of the body. The first analysis was performed to examine changes in shank kinetic energy and the second analysis was performed to examine changes in thigh kinetic energy. The kinetic energy measures were selected at the points of foot strike (FS), midstance (MS) and toe off (TO) and served as the dependent variables for these analyses. Three effects were tested in these analyses: main effect of subject, main effect of run, and effect of side within trial within run.

The results of these analyses will be discussed in this section. A probability level of .1 was established for the determination of statistical significance.

The first four multivariate analysis of covariance analyses examined changes in kinetic energy measures at LFS, LMS, LTO, RFS, RMS and RTO. These analyses were performed to examine changes in the kinetic energy of the left shank, left thigh, right shank and right thigh.

A two-way multivariate analysis of covariance analysis evaluating changes in left shank kinetic energy at the selected points throughout the cycle of the run indicated a significant main effect of subject ($F=2.43$, $p<.001$) and a significant main effect of run ($F=2.66$, $p<.001$). The significant main effect of run indicated that while controlling for initial differences in the velocities of the four runs for each subject, differences in kinetic energy measures existed for at least one of the six dependent variables for the left shank. Examination of the univariate F-tests for the six dependent variables for the main effect of run indicated significant differences at LMS ($F=3.49$, $p<.023$) and RMS ($F=5.38$, $p<.003$). The effect of trial within run also was found significant ($F=1.55$, $p<.004$). The significant main effect of trial within run suggested that changes in kinetic energy measures existed between trials in the thirty minute, constant velocity runs for at least one of the six dependent variables for the left shank. Examination of the univariate F-tests for the dependent variables indicated a significant difference at LFS ($F=2.65$, $p<.005$).

The second analysis examined changes in the kinetic energy of the left thigh. The main effect of subject was significant ($F=1.63$, $p<.041$), and the main effect of run was significant ($F=2.61$, $p<.001$). The significant main effect of run indicated that while controlling for initial differences in the velocities of the four runs for each subject, differences in kinetic energy measures existed for at least one of the six dependent variables for the left thigh. Examination of the univariate F-tests for the main effect of run yielded significant differences at LFS ($F=3.15$, $p<.034$), RFS ($F=2.78$, $p<.051$) and RMS ($F=3.66$, $p<.019$). The effect of trial within run was significant ($F=2.05$, $p<.0001$) indicating that changes in kinetic energy measures existed between trials in the thirty minute, constant velocity runs for at least one of the six dependent variables for the left thigh. Examination of the univariate F-tests indicated a significant difference at LFS ($F=3.30$, $p<.001$).

For the third analysis changes in the kinetic energy of the right shank were examined. The main effect of subject was significant ($F=2.68$, $p<.0001$) and the main effect of run was significant ($F=2.40$, $p<.003$). The finding of the significant main effect of run indicated that while controlling for initial differences in the velocities of the four runs for each subject, differences in kinetic energy measures of the right shank existed for at least one of the six dependent variables. The examination of the univariate F-tests for the main effect of run indicated that significant differences existed at LFS ($F=3.64$, $p<.012$), LTO ($F=4.96$, $p<.002$), RFS ($F=8.02$, $p<.0001$) and RMS ($F=2.58$, $p<.049$). The effect of trial within run was significant ($F=1.58$, $p<.003$) which indicated that changes in kinetic energy measures existed between trials in the thirty minute, constant velocity runs for at least one of the six dependent variables for the right shank. Examination of the univariate F-tests indicated significant differences at LFS ($F=3.31$, $p<.001$) and RFS ($F=1.71$, $p<.077$).

The fourth analysis examined changes in the kinetic energy of right thigh. The main effect of subject was significant ($F=2.16$, $p<.003$) and the main effect of run was significant ($F=1.57$, $p<.078$). The finding of a significant main effect of run indicated that while controlling for initial differences in the velocities of the four runs for each subject, differences in kinetic energy measures existed for at least one of the six dependent variables for the right thigh. The results of the univariate F-tests for the main effect of run indicated a significant difference at LMS ($F=3.86$, $p<.015$). The effect of trial within run was not significant ($F=1.20$, $p<.133$).

The final two way multivariate analysis of covariance analyses were performed to examine changes between the left and right sides of the body at the selected points of FS, MS and TO. The first analysis examined changes in shank kinetic energy. The main effect of subject was significant ($F=3.33$, $p<.0001$) and the main effect of run was also significant ($F=2.57$, $p<.007$). Finding of a significant main effect of run indicated that while controlling for initial differences in the velocities of the four runs for each subject, differences existed for at least one of the six dependent variables for the shank. Examination of the univariate F-tests for the main effect of run indicated significant differences at TO ($F=3.48$, $p<.018$). The effect of side within trial within run was not significant.

The second analysis examined changes in thigh kinetic energy. The main effect of subject was significant ($F=2.80$, $p<.001$). The main effect of run was not found significant. The effect of side within trial within run was also not significant.

A significant main effect of run was found for each of the four multivariate analysis of covariance analyses which examined the changes in bilateral thigh and shank kinetic energy measures at the selected events of LFS, LMS, LTO, RFS, RMS and RTO. A significant main effect of run indicated that while controlling for initial differences in the velocities of the four runs for each subject, differences in kinetic energy measures existed for at least of one of the six dependent variables. Examination of the univariate F-tests for the six dependent variables in these four analyses, yielded ten significant differences. Five significant differences occurred during the swing phase, four occurred during the support phase and one occurred during the nonsupport phase. Examination of the univariate F-tests for the shank indicated that three significant differences were detected during the support phase, two during the swing phase and one during the nonsupport phase. Examination of the univariate F-tests for the thigh indicated that one significant difference occurred during the support phase and three during the swing phase. In summary, the shank kinetic energy was found to be significantly different in both the support and the swing phases, while the thigh kinetic energy was more variable during the swing phase. Of the six dependent variables that were significantly different for the main effect of run, the RMS was significantly different in three of the four analyses. Only the omnibus F-tests could be reported, since limitations imposed by the design of the study prevented further post hoc testing.

A significant main effect of trial within run was found for three of the four multivariate analysis of covariance analyses in which the changes in bilateral thigh and shank kinetic energy measures at LFS, LMS, LTO, RFS, RFS and RTO were examined. The effect of trial within run was not significant for the analysis examining the kinetic energy measures of the right thigh. A significant main effect of trial within run indicated that changes in kinetic energy measures existed between trials in the thirty minute, constant velocity runs for at least one of the six dependent variables. An examination of the univariate F-tests for these three analyses indicated four significant differences. One of these significant differences occurred during the swing phase. Examination of the univariate F-tests for the shank indicated that two significant differences occurred during the support phase and one during the swing phase. Examination of the univariate F-tests for the thigh indicated that one significant difference occurred during the support phase. Consequently, when the kinetic energy measures of the thigh and shank were examined by trial within run, no apparent pattern was evident as to which segment varied more for the six dependent variables. Of the six dependent variables utilized in these analyses, the kinetic energy at LFS was significantly different in three of the four analyses. It was interesting to note that only the kinetic energy measures at foot strike (LFS and RFS) were significantly different for the effect of trial within run.

One significant main effect difference was found in the two multivariate analysis of covariance analyses that were used to examine differences in kinetic energy between the right and left sides of the body at the points of foot strike, midstance and toeoff. The main effect of run was significantly different for the analysis when the right and left shank kinetic energies were compared. Examination of the univariate F-tests indicated that the kinetic energy at TO was significantly different. The analysis comparing the right and left thigh kinetic energy measures indicated that there was no significant main effect of run. The interaction effect of side within trial within run for kinetic energy was not significant for both the thigh and the shank. Therefore, while controlling for initial differences in the velocities of the four runs for each subject, differences between right and left shank kinetic energy existed at toeoff.

In summary, significant differences in the kinetic energy measures of the shank occurred most often when this segment was in the support phase. Significant differences in the kinetic energy of the thigh occurred most often when this segment was in its swing phase. Differences between right and left sides of the body were not significant. Only the results of the omnibus F-tests could be reported since limitations imposed by the design of the study prevented further post hoc testing.

Kinetic energy analysis

The purpose of this study was twofold: 1) to examine the process of fatigue by determining if differences in bilateral kinetic energy patterns of the thigh and shank existed as distance runners fatigued if the velocity of the run was held constant and 2) to determine if differences in bilateral kinetic energy patterns of the thigh and shank coincided with changes in the ventilatory equivalent for oxygen uptake. The results indicated that differences existed across the four, thirty minute, constant velocity runs and within the trials of these runs, however, the nature of the differences remained unclear. The graphs for bilateral kinetic energy measures were examined in order to determine the nature of these differences. A discussion of the changes in the bilateral kinetic energy patterns of the thigh and shank will be presented in this section. Since similarities existed between subjects, only one subject's data (subject 5) will be presented. Graphs of these data for subjects 1-4 may be obtained from the School of HCP, Michigan State University, East Lansing, Michigan.

Changes in the kinetic energy patterns of the right and left thighs and shanks were found to occur for all subjects as each runner fatigued. Individual differences between subjects were noted, but general patterns of decreases in the magnitudes of kinetic energy and erratic changes in the magnitudes of kinetic energy emerged in the data which were evident for all subjects. Therefore, the data from one representative subject was presented to illustrate these changes.

The kinetic energy patterns for the left thigh and shank for subject 5 for run A can be seen in Figures 7a-b. Little variation in the magnitude of kinetic energy was noted across trials. The kinetic energy measures across trials for the right thigh and shank can be seen in Figures 8a-b. The magnitudes of the segmental kinetic energy were consistent across trials with the exception of the kinetic energy of the right shank at LMS in trial 5. This isolated increase could be due to measurement error.

The graphs of the kinetic energy of the left thigh and shank for the 1B run are presented in Figures 9a-b. Variation was evident in the support phase at LMS and during the swing phase at RFS. The kinetic energy measures of the right thigh and shank are presented in Figures 10a-b. The kinetic energy patterns were consistent with the exception of the right thigh at LMS in trial 5 and the right shank at RTO in trial 1. More variation in the magnitudes of kinetic energy was noted in the swing phase across trials for both subjects as compared to the support phase.

The kinetic energy patterns of the left thigh and shank for the 2B run are displayed in Figures 11a-b. Erratic increases and decreases in kinetic energy were evident during the swing phase for both segments. The left thigh kinetic energy was erratic at RFS and RMS, while the kinetic energy of the left shank was erratic at RMS and RTO. Examination of the kinetic energy patterns of the right thigh and shank will be found in Figures 12a-b. A greater variability in kinetic energy patterning was found for the thigh kinetic energy during the swing phase and for the shank kinetic energy during the support phase than for the left thigh and shank.

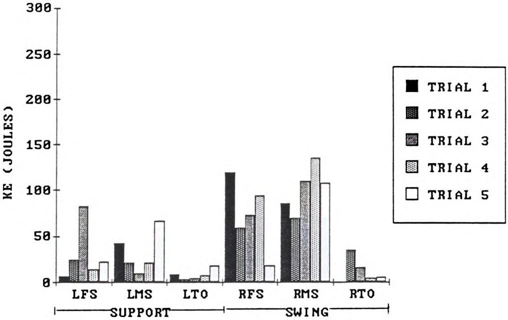

Figure 7a. Run A: Left thigh

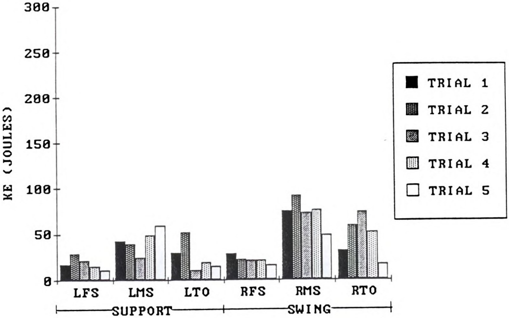

Figure 7b. Run A: Left shank

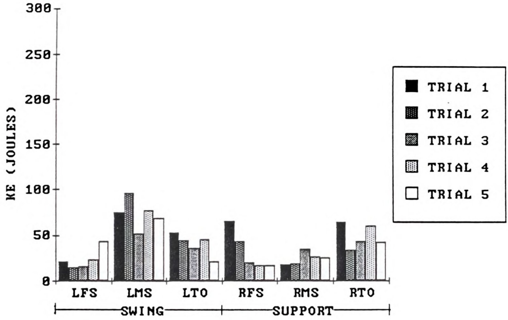

Figure 8a. Run A: Right thigh

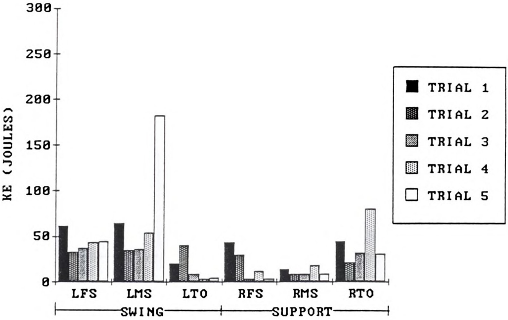

Figure 8b. Run A: Right shank

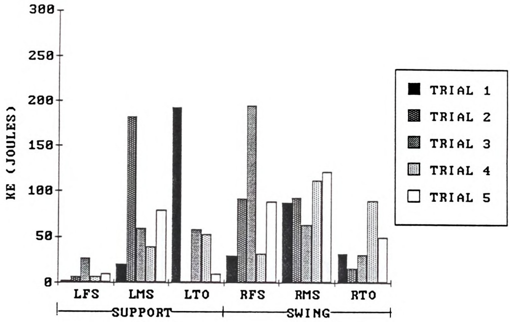

Figure 9a. Run 1B: Left thigh

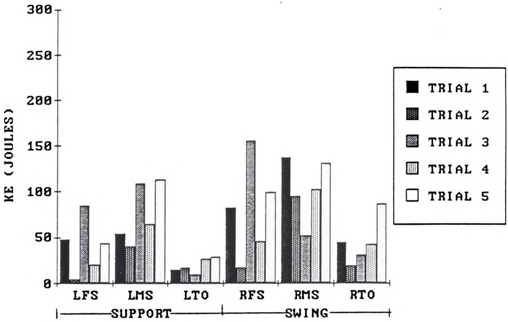

Figure 9b. Run 1B: Left shank

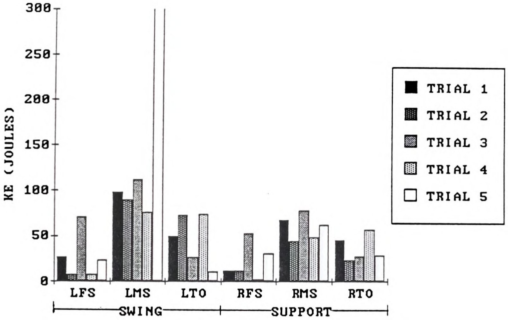

Figure 10a. Run 1B: Right thigh

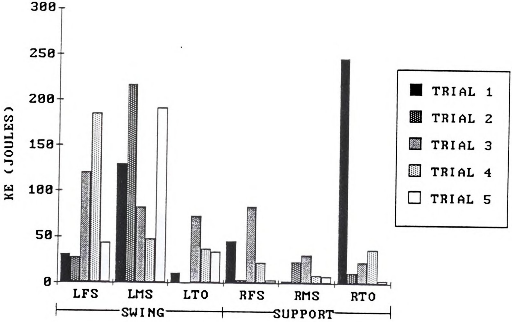

Figure 10b. Run 1B: Right shank

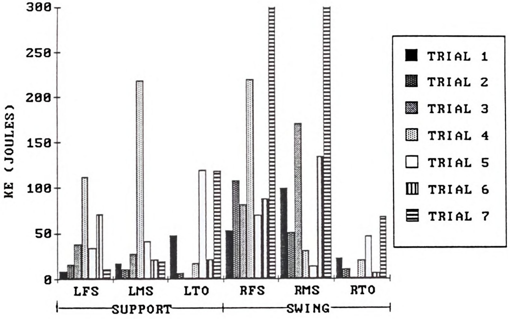

Figure 11a. Run 2B: Left thigh

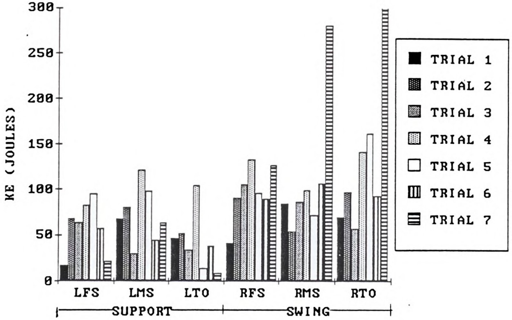

Figure 11b. Run 2B: Left shank

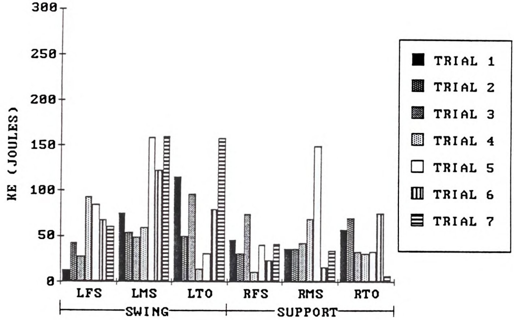

Figure 12a. Run 2B: Right thigh

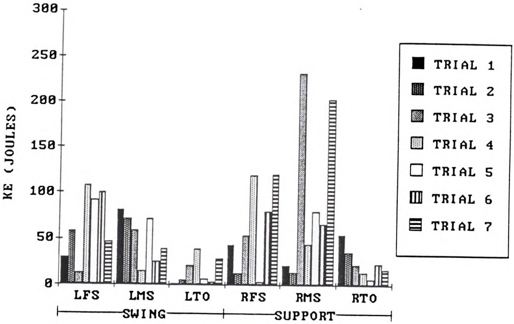

Figure 12b. Run 2B: Right shank

The kinetic energy patterns of the left thigh and shank for run C can be found in Figures 13a-b. The data for trial 2 were eliminated due to film over exposure resulting in decreased confidence in accurate locations of joint markers during the data reduction phase. A pattern similar to the 2B run wa evident in that there was more variation in the kinetic energy of both segments during the swing phase when compared to the support phase. The kinetic energy measures of the right thigh and shank were less variable than those measures for the left leg (Figures 14a-b).

In summary, as the runners fatigued, changes were noted in patterning of the bilateral thigh and shank kinetic energy values. First, there tended to be a general decrease in the kinetic energy of both segments across trials. An erratic pattern of abrupt increases and decreases in kinetic energy followed the period of decreased kinetic energy. This pattern was evident in both the support and recovery phases of both legs and suggested that the subject's ability to move the thigh and shank segments throughout the movement phase was being impaired by the onset of fatigue. Moreover, there was more variability in the swing phase when compared to the support phase. This variability in the swing phase may have indicated that the subject attempted to maintain the velocity of the run dictated by the treadmill, by attempting to swing the recovery leg through its range of motion faster.

Erratic patterns in segmental kinetic energy have been found in less skilled performance (Evans, 1982; Garrett, 1970; Ulibarri, 1981). Evans (1982), in a study evaluating the overhand throwing pattern between skilled and less skilled throwers found abrupt peaks

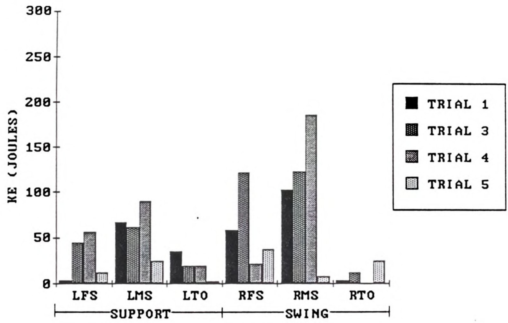

Figure 13a. Run C: Left thigh

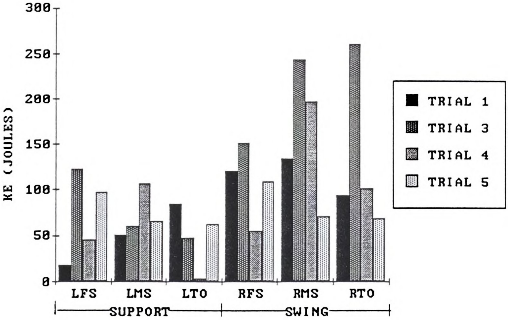

Figure 13b. Run C: Left shank

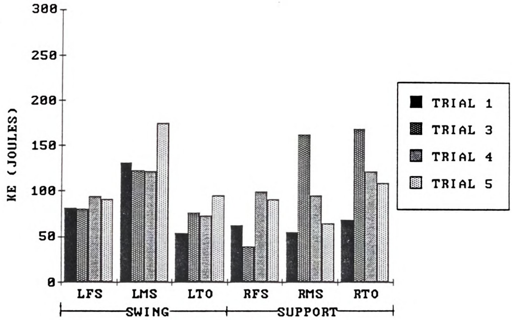

Figure 14a. Run C: Right thigh

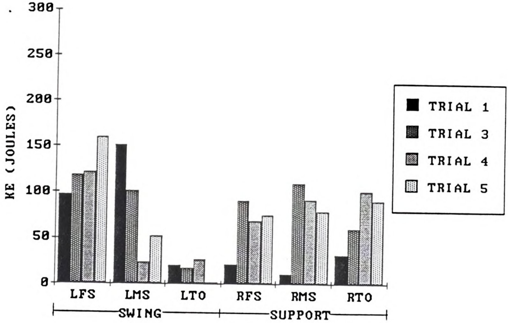

Figure 14b. Run C: Right shank

in the segmental kinetic energy patterns of the less skilled throwers. Evans (1982) concluded that these abrupt changes in the segmental kinetic energy patterns were due to the less efficient coordination of segmental motions in the less skilled throwers. Ulibarri (1981) found erratic patterns in the kinetic energy curves of the bat for less skilled softball batters when compared to highly skilled batters. Ulibarri concluded that the erratic patterns displayed by the less skilled batters were due to inefficient summation of forces by these less skilled batters.

The erratic pattern of kinetic energy of both segments that followed the decrease in kinetic energy across trials indicated that the runners' effort to maintain running at each constant treadmill velocity resulted in inefficient and uncoordinated movement patterns due to the onset of fatigue. This erratic pattern was especially evident in the swing phase.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to examine the process of fatigue in distance runners. Five trained male runners comprised the sample for this study. Initially, in order to determine ventilatory breakpoints, each subject participated in a continuous, incremental treadmill run to exhaustion. The test began with the treadmill velocity set at 2.28 m/sec. The velocity was increased 0.13 m/sec each minute. Expired gases were collected and analyzed for oxygen and carbon dioxide concentrations. Heart rate response was recorded at approximately thirty second intervals. The test continued until terminated by the subject. Pre and post run blood lactates were determined.

The $\dot{V}E/\dot{V}O_2$ values obtained from this initial test were plotted against treadmill velocity. The point at which the slope of the $\dot{V}E/\dot{V}O_2$ graph changed was labeled ventilatory breakpoint 1. The second change in the slope of this graph was labeled ventilatory breakpoint 2. Treadmill velocities that corresponded to the two breakpoints were determined. Velocities of 0.13 m/sec above and below each breakpoint were determined for each subject.

Each subject ran four, thirty minute, constant velocity runs (A, 1B, 2B and C) at their predetermined velocities. Standard cinematographic techniques were utilized to obtain film data from the four runs. For the A and 1B runs, filming occurred every six minutes beginning at 5:30 minutes into the run. For the 2B and C runs, filming occurred at three minute intervals beginning at 2:30 minutes into the run.

The film was digitized using an ALTEK rear projection system and the occurrance of left and right foot strike, midstance and toeoff were visually determined and recorded. Segmental kinetic energy values were calculated for each data set utilizing a FORTRAN program.

Multivariate analysis of covariance procedures were used to evaluate changes in bilateral segmental kinetic energy measures at left foot strike, left midstance, left toeoff, right foot strike, right midstance and right toeoff. A significant main effect of run was found for each of the four multivariate analysis of covariance procedures. A significant main effect of run indicated that while controlling for initial differences in the velocities of the four runs for each subject, differences in kinetic energy measures existed for at least one of the six dependent variables. Examination of the univariate F-tests for the six dependent variables for these four analyses indicated ten significant differences. Five differences occurred during the swing phase, four occurred during the support phase and one occurred during the nonsupport phase. Examination of the univariate F-tests for the shank indicated that three significant differences were detected during the support phase, two during the swing phase and one during the nonsupport phase. Examination of the univariate F-tests for the thigh indicated that one significant difference occurred during the support phase and three during the swing phase. Consequently, the shank kinetic energy measures were significantly different in both the support and swing phases while the thigh kinetic energy values were more variable during the swing phase.

A significant main effect of trial within run was found for the left thigh and shank and for the right shank. The effect of trial within run was not significant for the analysis examining the kinetic energy measures of the right thigh. A significant effect of trial within run indicated that changes in kinetic energy measures existed between trials in the thirty minute, constant velocity runs for at least one of the six dependent variables. An examination of the univariate F-tests for these three analyses indicated four significant differences. Examination of the univariate F-test for the shank indicated that two significant differences occurred during the support phase and one during the swing phase. Examination of the univariate F-tests for the thigh indicated that one significant difference occurred during the support phase.

One significant main effect difference was found in the two multivariate analysis of covariance analyses that were used to examine differences between the right and left sides of the body at the points of foot strike, midstance and toeoff. The main effect of run was found to be significantly different for the analysis comparing the right and left shank kinetic energy values. Kinetic energy values at toeoff were significantly different as indicated by the univariate F-tests. The analysis comparing right and left thigh kinetic energy measures were not significant. The interaction of side within trial within run was not significant for either the thigh or the shank.

In summary, both hypotheses tested in this study were accepted. The first hypothesis tested was that there were significant differences in bilateral kinetic energy measures of the thigh and shank as a runner fatigued when the velocity of the run was held constant. The second hypothesis tested was that there were significant differences in bilateral kinetic energy measures of the thigh and shank in the selected constant velocities that coincided with changes in the ventilatory equivalent for oxygen uptake. Furthermore, significant differences in the kinetic energy measures of the shank occurred in the support and swing phases. Significant differences in the kinetic energy values of the thigh occurred most often in the recovery phase. Differences in kinetic energy between right and left sides of the body at foot strike, midstance and toeoff were found to be not significant.

An examination of the pattern of bilateral thigh and shank kinetic energy measures across trials indicated that as a runner fatigued, there was an initial decrease in the magnitudes of the thigh and shank kinetic energies. This decrease was followed by a pattern of erratic increases and decreases in kinetic energy especially during the later trials in the 2B and C runs. More variability in kinetic energy values was evident in the swing phase than the support phase. The variability in the swing phase may be due to each runner's attempt to maintain running at the constant treadmill velocity as each subject fatigued. Furthermore, this variability was evidenced by rapid and erratic movements of the thigh and shank primarily during the swing phase. In conclusion, this pattern of kinetic energy was indicative of inefficient movement patterns due to the onset of fatigue.

Conclusions

The following conclusions may be drawn from the results of this study.

1. Use of a segmental kinetic energy analysis detected changes in the kinetic energy patterns of the right and left thigh and shank in trained male distance runners as they responded to fatigue while running at a constant velocity.
2. While the velocity of the run was held constant, and the runners fatigued, erratic patterns in bilateral kinetic energies were noted. This erratic pattern of segmental kinetic energies were determined to be due to inefficient and uncoordinated movements which resulted from the onset of fatigue.
3. The graph of the ventilatory equivalent of oxygen uptake was the most sensitive measure for detecting each subject's inability to maintain a steady state work rate in the thirty minute, constant velocity runs.
4. The collection of physiological data in conjunction with biomechanical data collection is essential in investigations of fatigue to enable quantification of the physiological state of the runner.

5. Finally, it may be more appropriate to normalize the data by physiological parameters such as ventilatory breakpoints, rather than by velocity.

Recommendations

1. Future studies investigating the effects of fatigue in running should employ different skill levels as well as females to observe if similar responses to fatigue are elicited by these different groups.
2. Interdisciplinary studies examining both biomechanical and physiological aspects of running performance should normalize using physiological parameters in order that the velocities at which each subject should run can be determined.
3. A segmental kinetic energy approach should be utilized in the investigation of the effects of fatigue in other endurance type events.

APPENDIX

WRITTEN INFORMED CONSENT STATEMENT

1. I have freely consented to take part in a scientific study on fatigue effects of running conducted by Sharon Evans under the direction of Drs. Ulibarri and VanHuss.

2. I understand that this is a research project being conducted to study biomechanical and physiological effects of fatigue while running. I understand that to perform this analysis the following measurements will be taken:

   a. I will be filmed as I run on a level treadmill.

   b. I will be required to attend four filming sessions at which time the treadmill speed will be set at a predetermined constant speed.

   c. I will anticipate running on the treadmill for 30 minutes at each session.

   d. My body weight will be obtained from a scale.

3. I understand that in the unlikely event of injury resulting from research procedures, Michigan State University, its agents, and employees will assume that responsibility as required by law. Emergency medical treatment for injuries or illness is available when the injury or illness is incurred in the course of an experiment. I have been advised that I should look toward my own health insurance program for payment of said medical expenses.

4. I understand that I am free to discontinue my participation in the study at any time without penalty.

5. I understand that data from my performances may be used for demonstrations, instruction, and study.

6. I understand that my name will not be used in any publication, presentation, or discussion of data based upon my performances.

7. I understand that I will receive a copy of my individual results, and that I can receive additional information about this study or these results after my participation is completed.

Date ______________________ Signed ___________________________

Witness ___________________ Address __________________________

____

Phone Number _____________________

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REFERENCES

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